THE DEVELOPMENT OF GIS TO AID CONSERVATION OF ARCHITECTURAL AND ARCHAEOLOGICAL SITES USING DIGITAL TERRESTRIAL PHOTOGRAMMETRY

BY

SEYED YOUSEF SADJADI

B.Sc. in Physics (Tehran University, Iran) 1973
M.Sc. in Surveying Engineering (KNT University of Technology, Iran) 1977

A Thesis for the Degree of Doctor of Philosophy (Ph.D.)

December 2005

ABSTRACT

This thesis is concerned with the creation and implementation of an Architectural/Archaeological Information System (A/AIS) by integrating digital terrestrial photogrammetry and CAD facilities as applicable to the requirements of architects, archaeologists and civil engineers.

Architects and archaeologists are involved with the measurement, analysis and recording of the historical buildings and monuments. Hard-copy photogrammetric methods supporting such analyses and documentation are well established. But the requirement to interpret, classify and quantitatively process photographs can be time consuming. Also, they have limited application and cannot be re-examined if the information desired is not directly presented and a much more challenging extraction of 3-D coordinates than in a digital photogrammetric environment.

The A/AIS has been developed to the point that it can provide a precise and reliable technique for non-contact 3-D measurements. The speed of on-line data acquisition, high degree of automation and adaptability has made this technique a powerful measurement tool with a great number of applications for architectural or archaeological sites. The designed tool (A/AIS) has been successful in producing the expected results in tasks examined for St. Avit Senieur Abbey in France, Strome Castle in Scotland, Gilbert Scott Building of Glasgow University, Hunter Memorial in Glasgow University and Anobanini Rock in Iran.

The goals of this research were:

- to extract, using digital photogrammetric digitising, 3-D coordinates of architectural/archaeological features,
- to identify an appropriate 3-D model,
- to import 3-D points/lines into an appropriate 3-D modeller,
- to generate 3-D objects,

- to design and implement a prototype architectural Information System using the above 3-D model,
- to compare this approach to traditional approaches of measuring and archiving required information.

An assessment of the contribution of digital photogrammetry, GIS and CAD to the surveying, conservation, recording and documentation of historical buildings and cultural monuments include digital rectification and restitution, feature extraction for the creation of 3-D digital models and the computer visualisation are the focus of this research.

Declaration

I, Seyed Yousef Sadjadi declare this thesis is the product of my work, except where indicated, and has not been submitted by myself or any other person for any degree at this or any other university.

Seyed Yousef Sadjadi
January 5th, 2006

ACKNOWLEDGEMENTS

The author would like to express his sincere gratitude to Dr. Jane Drummond, the senior lecturer at the University of Glasgow in the UK for her supports to proceed with the "Honorary Research Associate" for one year by the Glasgow School of Architecture towards the AHRB project at St. Avit in France in year 2000 and also to provide the PhotoModeler software for his use and her kind directions, supports, encouragements and advices throughout this research study. Her patience in reading and correcting the Chapters and brightening the confusions and misunderstandings is really appreciated.

Throughout this research, the author received assistance and advice from staff members and postgraduate colleagues. In particular, the author is very thankful to his previous research colleague, Dr. Alias Abdul-Rahman, the former PhD student at the University of Glasgow for his assistance and advice on the use of the tools in the GIS while he was available and studying, Mr. Les Hill for his interest and assitance about the photography during the St. Avit project in France and other tasks at Glasgow University.

Finally, but not the least, the author is greatly indebted to his wife and sons for their patience and understanding throughout this study.

Seyed Yousef Sadjadi, B.Sc, M.Sc

Khaje Nasir Tousi University of Technology
Faculty of Civil Engineering
Department of Surveying
Tehran, Iran

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1. Introduction

1.1 Background

In projects involving surveying and documenting the archaeological and architectural heritage of a region, fast, accurate and relatively inexpensive methods of data capture, analysis or representation may have to be available, particularly as such projects often emerge unexpectedly and need to be dealt with rapidly [Robson *et al.*, 1994], [Ogleby, 1995]. During the investigations reported in this thesis, the author, who has a land-surveying background, has been privileged to collaborate with archaeologists and architects involved with the measurement and analysis of the remains of castles, churches, rock sculptures and other major structures in Scotland, France and Iran. Hard-copy photogrammetric approaches to supporting such analyses are well established [Ogleby, 1995]; indeed the primary data capture is fast and the resulting archive produced potentially invaluable, but the requirement to interpret, classify and quantitatively process photographs can be a time consuming task which requires highly experienced personnel. Their absence, at a particular point in time, may result in information of inadequate accuracy or timeliness.

Are there alternatives to the conventional hard-copy photogrammetric approaches?

One alternative is laser scanning. This is a rapidly emerging technology [Bryan and Blake, 2000], but it did not, for example, appeal to the collaborating architects, historians and archaeologists, who worked with the author and who indicated that to have an archive of photographic images of important cultural objects would be almost essential. It should, however, be noted that in Glasgow University the basic surveying of a nineteenth century listed building very severely damaged by fire, in 2000, has used laser scanning [Dallas and Morris, 2002], and that English Heritage has recently published guidelines for the use of laser scanning for the protection of historic buildings [Barber *et al.*, 2003]. (See Appendix E for a brief summary of laser scanning.)

Another alternative to hard-copy photogrammetry is soft-copy or digital photogrammetry, and the author's collaborators felt comfortable with this. The technical reasons for considering soft-copy photogrammetry include:

- convenient measurement and re-measurement;
- accuracy;
- cost; and,
- potential of photo-realistic modelling.

Considering convenient measurement and re-measurement, traditionally, hard-copy photogrammetry for archaeological and architectural applications has produced 2-D building elevations drawings and large-scale planimetric maps [Fraser, 1993] of predictable accuracy. Whilst these plans constitute a useful record, they have limited application and cannot be interrogated further if the information desired is not directly presented. These limitations mean that the available information relates to matters of importance current at the time of measurement, but is inadequate for answering questions that may be raised later and by other workers. It will be necessary for the archaeologist to make a time-consuming return to the photogrammetrist for the additional information. Soft-copy photogrammetry produces digital orthophotos (possibly with their stereo mates), which allow a three-dimensional spatial model of photographed surfaces to be viewed, and from which accurate measurements can be rapidly made, by a non-photogrammetrist. That the orthophotos and their stereo mates can be archived (e.g. in an information system) ready for immediate use represents a great timesaving over hard-copy approaches. Re-measurement in the hard-copy environment involves the time consuming re-orientation of the original photos in a stereo plotter and a much more challenging extraction of 3-D coordinates than in a digital photogrammetric workstation where (for example) the correction for x-parallax can be automatic. Thus, without inconvenience, the object can continue to be studied or re-studied, or can be reconstructed. Realistically the original photographs can also be archived and accessed for reprocessing through user friendly digital photogrammetric procedures, should stored digital orthophotos prove inappropriate, for example by being at the wrong resolution.

Turning to accuracy, digital photogrammetry has matured to the extent that it can now serve as a precise and reliable technique for non-contact 3-D measurements. Its ease and speed of data acquisition, inherent on-line and even real-time capabilities, high degree of automation and adaptability have made it a powerful measurement tool with a great number of applications in science, art and industry. In terms of accuracy, experienced practitioners confirm that hard copy photogrammetry gives results as good as soft copy. However it is the less experienced practitioners (such as found in groups of archaeologists, historians and architects) with whom this work is concerned; the lower 'skill' levels required of soft copy photogrammetry are likely to produce better results from the operators.

At both the conceptual and implementation levels digital photogrammetry permits properties of high precision and reliability to be merged with dynamic data acquisition and processing. Nevertheless, the required accuracy and the realised accuracy of such systems must be considered. Although terrestrial photogrammetric techniques appear to have great potential in the documentation of buildings the main requirement remains the restitution or remediation of buildings to a sufficient degree of detail and accuracy for the purpose, in a cost-effective manner.

Considering cost, Bähr and Wiesel [1991] believed that low-cost workstations and scanners would grant useful economic solutions to digital processing and eventually produce a product of the quality formerly expected from (hard copy) analytical plotters. In the case of digital photogrammetry, digital scanners are used if good digital cameras are not available. Both low-end (PhotoModeller or PMP, the acronym by which it is frequently referred in this thesis) and high-end systems (SOCET) have been used in this study, but as formerly high-end systems become less expensive, price is not particularly considered an issue. Fifteen years ago the high-end digital photogrammetric system of the type used in this study was only available in the defence sector (with corresponding budgets) but now similar systems are regularly being bought by less well-funded organisations, including academic archaeology departments [Cooper *et al.*, 1992].

In the past, to overcome some of the visualisation limitations of 2-D drawings controlled photo mosaics, of e.g. buildings, were produced by rectification [Walker, 1996]. These, of necessity, represented almost plane façades. Later, the differential rectification method of analogue orthophotography was employed [Weng *et al.*, 1992]. But even this procedure had its limitations, as surface structures with continuous shape were presupposed. Strong discontinuities on façades were difficult to manage. Façades had to be subdivided into limited plane facets (facet - a little face; a small, plane surface: from dictionary LaborLawTalk.com) and other surfaces [Sawyer and Bell, 1994].

The generation of photo-realistic 3-D models seems an obvious way to support archaeologists and architects. Digital photogrammetry supports the production of photo-realistic 3-D models by being able to supply 3-D coordinates, orthophotos and a Digital Surface Model (DSM). The 3-D coordinated points can be used to construct a model and these coordinated points can be augmented by others captured from orthophotos with a complementary DSM. Digital Photogrammetry supplies texture information from its orthophotos, which can be used in rendering, and shape information from its DSMs.

Digital photogrammetric packages enable the user to perform the whole reconstruction of the 3-D object without any manual measurement apart from that required for control [Cooper and Robson, 1994]. Digital photogrammetry allows the all-around 3-D representation of a building. It allows interpretation of the scene qualitatively while selecting the features to be measured; the software performs the quantitative measurement and calculations. Digital photogrammetric packages do provide limited CAD functionality, but of course their main strength is their photogrammetric functionality. 3-D coordinates captured in a digital photogrammetric workstation can be exported to a CAD system. A CAD system (such as AutoCAD or the CAD tools of a Geographical Information System package such as ArcVIEW/ArcGIS) supplies the draughting and analytical tools needed.

However the products of digital photogrammetry (orthophotos, stereo mates, orthophotomosaics, DSMs) need archiving, and they need to be accessed rapidly from this archive. Novel visualisations, such as showing different architectural epochs, the generation of quantitative descriptors (such as calculations of area, volume, slope or curvature), simultaneous access to a range of maps or documents, etc., are further tools enhancing the work of archaeologists and architects. These enhancements point to the usefulness of spatial information system technology.

Geographical Information Systems (GISs) represent a highly relevant branch of information technology. GISs support the import of geospatial data from a variety of sources, including imagery. An appropriate environment for providing the spatial information needed by architects working with historic buildings and archaeologists might be soft-copy photogrammetry coupled with, or linked to, GIS, forming an Archaeological/Architectural Information System (A/AIS). Reasons for this relate to the already mentioned, relative simplicity of digital photogrammetry procedures, widespread knowledge and understanding of certain off-the-shelf GIS packages and the scarcity of personnel and equipment capable of performing hard-copy photogrammetric tasks.

Technical reasons for considering a GIS package as a component of the A/AIS include:

- An accessible archive management system
- Visualisation tools
- CAD tools
- Use of a world coordinate system
- Data base tables linked to graphic objects, and the appropriate SQL

But CAD packages too can, under some circumstances, support all the above, and also (unlike off-the-shelf GIS) tend to handle 3-D coordinates as standard. Thus, although CAD and GIS packages have their separate distinctive functionality, there is common functionality which is very relevant to the management of archaeological and architectural structures. For this reason in some of the investigations discussed in this thesis, an information system built on a GIS (ArcGIS) is considered whereas in others a CAD package (AutoCAD) is considered.

As well as orthophotos, computerised documentation (pictures, plans, derived measurements, historical notes, details of building materials) of the original cultural objects could be archived, or even generated, using the information system.

Thus for modern digital photogrammetric methods to be applied, it is necessary to build up an archive of terrestrial photographic images, with appropriate details of the characteristics of the photography, for documenting the façades of buildings. From this archive the relevant measurements can be taken to create a geospatial database. Orthophotos (and stereomates and orthophoto mosaics) can be generated and they too can then be integrated into the growing information system. Then information (such as construction materials, textural information, building methods, business models such as those used to generate information on repair and maintenance costs etc.) can be gathered and stored with the existing geospatial database to create an extremely useful information system. This information is combined to model the cultural object.

For example, using the stored data of an A/AIS, plots can be displayed at any scale and in colours according to their thematic content. Corresponding or adjoining walls, shapes and gaps can be detected and the originals reinstated, certain elements can be defined and the decorative features (see Figure 1.1 for an example), scripts, murals, etc. can be completed or reconstructed by using known representations and texts (such as religious texts). By processing orthophotos (for example processed from data captured by photogrammetric cameras), true scale images (of smaller features) can be produced, greatly assisting renovation.

In such a proposed system the graphical representation utilises line drawings and orthophotos. The line drawings emphasise the object's geometry, which allows interpretation of the architectural history and the representation of features to a desirable degree of abstraction. The actual inventory of e.g. a building can be shown, in more detail and without interpretation, by orthophoto mosaics; likewise decay too can be shown. Thus it can be understood that a combination of both line drawing and orthophoto mosaics is preferable, as it gives a better representation of the state of a building.

Or, in the case of fire or other damage to a building containing repeated elements (such as arches, columns or friezes), sometimes only small or partial examples of detail remain, but by combining photogrammetry with CAD tools (found either in specialist packages such as AutoCAD or as CAD tools within a GIS), this detail can be recorded and projected to reproduce the original design. In this method of reconstruction, the redesign costs may be reduced and the refurbishment more accurate.

From the foregoing it can be seen that soft-copy photogrammetry and GIS present attractive tools and solutions to the problems experienced by archaeologists, historians and architects concerned with historic buildings, and other objects. However it is necessary to investigate the strengths and weaknesses of these tools and solutions, if it is to be certain that the proposed A/AIS meets the needs of the proposed users.

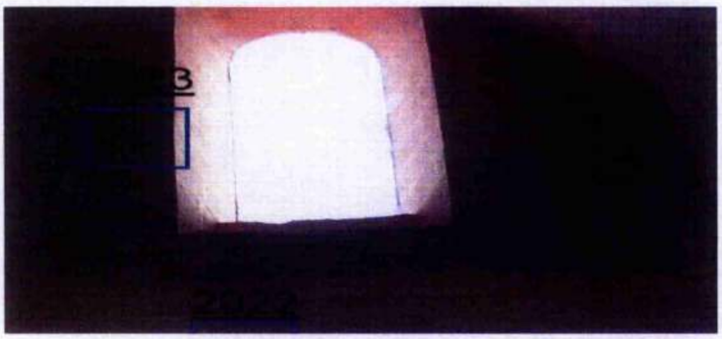
1.2 General Aims and Objectives

Society can hardly now turn its back on digital systems. The author, a land-surveyor, has been keen to explore digital systems, in this investigation, while noting that personnel able to handle analogue (traditional) approaches are becoming rare. However, the analogue approach has some distinct characteristics that may still wait transfer to the digital environment, and some of these maybe useful to architects, historians and archaeologists. But, a consideration may be the spatial tasks currently carried out by architects, historians and archaeologists involved in protecting the cultural heritage. These must be adequately replaced within any new approach.

For example, currently, in the surveying and documentation of cultural buildings, there is a task to record the decorated walls of buildings (see Figure 1.1). Direct copying of photography onto transparent foils, with measured dimensions marked on these has been the usual way of doing this job. This manual processing of terrestrial images is time consuming and frequently inaccurate, but any proposed alternative method must handle this time consuming task of recording decoration adequately.

FIGURE 1.1

A Part of the Wall Decoration in the Deconsecrated Abbey of St. Avit



Another requirement is the development of automated measurement routines that are adapted to and satisfy the special needs of cultural heritage. Traditional elevation drawings are at a large scale and reliable measurements can be taken off these large-scale drawings, as long as the relevant object is represented. But what is the possibility for the reliable measurement of architectural features using digital photogrammetric procedures? The typical scale of an architectural plan is 1:50, or smaller. Based on a likely smallest line weight of 0.25mm, the most optimistic maximum positional error is likely to be 12.5mm. Any alternative must equal or improve on this. In this context the term 'most optimistic' assumes rigorous quality control standards have been applied to the production and use of the architectural plans; namely the true position of the feature is within the draughted line and any measurement to it is also made within the draughted line, which ensures a maximum positional error of the line width (0.25mm scaled by 1:50) of 12.5mm, in this example.

Assuming that errors are randomly distributed, these assumptions imply a precision (standard deviation) of about 4.1mm (0.41 cm), or 12.5 / 3, for the measurement system. Any new system developed to replace the traditional architectural drawing approach should achieve this. English Heritage, the body with responsibility for the preservation of the English cultural heritage, sets a similar requirement [Bryan and Blake, 2000].

Conservation work requires the identification and labelling of structures from different epochs or eras. Traditionally the architectural surveyor identified these, based on experience, and produced line work in appropriate colours (i.e. 'colour coding'). Can this experience based identification of epoch be adequately replaced in the proposed environment, perhaps with something quantitative – such as variation in curvature? It can be assumed that the 'layer' philosophy and colour palettes typically found in off-the-shelf CAD and GIS packages will support the 'colour coding'.

At times the digital approach may seem inadequate, but improvements to the digital approach are emerging, rapidly. An aspect of this investigation will be to identify these further enhancements of the proposed solution that are likely to make the approach increasingly useful to architects and archaeologists.

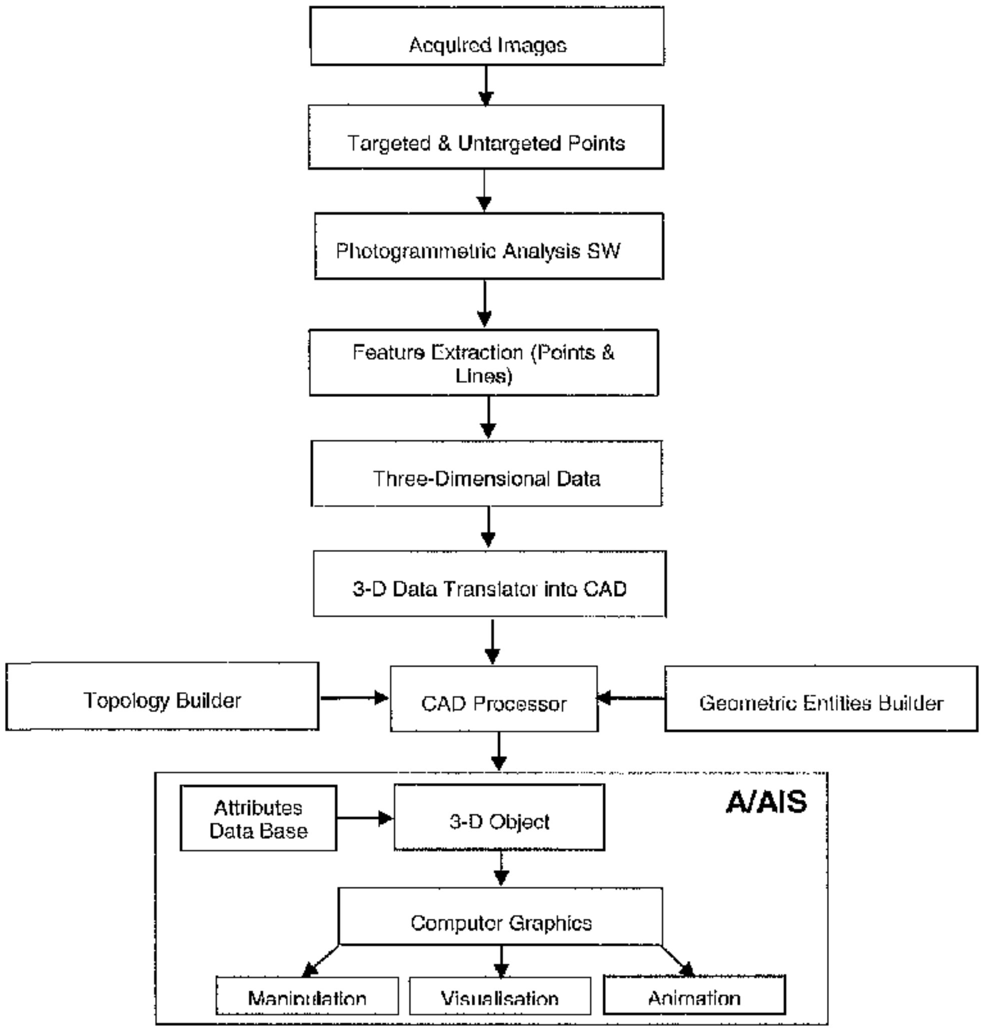
An information system developed specifically for archaeological or architectural work could be an expensive proposal. However, it is hoped that in this investigation a system built with relatively inexpensive components can be created. A representation of this proposed system is shown in Figure 1.2.

Thus the general aim of this study is to investigate the feasibility of developing an Archaeology/Architectural Information System (A/AIS) based on a fusion of Digital Photogrammetry, CAD and GIS. Although a great variety of real world objects (e.g. cars, bridges, human heads, etc.) could be described within such a system, the focus of this work is on buildings/structures. A/AIS Procedures which parallel or mimic those currently used by experienced practitioners are likely to be most effective.

While the general aim of this work will be met through investigating appropriate projects and relevant full or partial A/AIS implementations, this process can contribute to Geomatics in general if two particular objectives are achieved, namely:

FIGURE 1.2

Overview of the Proposed Archaeological/Architectural Information System (A/AIS)



1. to create digital models of cultural objects capable of supporting analysis in the chosen environment; and,

2. to specify the data content of digital images required for such models.

On completion of this investigation, it is hoped that the potential augmentation to the documentation and conservation of 3-D cultural objects (e.g. statues, monuments, archaeological relics, etc. but primarily buildings), supplied by the data capture functionalities of digital photogrammetry and the modelling and quantitative spatial analyses functionalities of GIS, will have been considered (i.e. identified and assessed) sufficiently by the author. This will enable him to be able to contribute to the development of well-founded systems for the archiving, interpretation and processing of photographs, documents and other data recording Iran's rich cultural heritage.

1.3 Research Tasks

As already stated the general aim of this work will be met through the process of investigating A/AIS implementations. There are several tasks, which the author has been involved in, which contribute to achieving the objectives. As mentioned in the previous section, one overall objective is to study methods to create realistic digital models of architectural objects. The other is to examine the data content of digital images required for such models.

The detailed tasks follow:

1. To identify the appropriate camera configuration and quality of measurement from the archaeological/architectural site.

2. To input the digitised co-ordinates into a 3-D model for further processing.

3. To build the 3-D model.

4. To design and implement prototype archaeological/architectural GIS (or A/AIS) environments by using the above 3-D model and the modelling facilities of a 3-D

drawing editor with a translator into a GIS file format. The A/AIS must exhibit the following capabilities:

- fast and comfortable data acquisition and processing;
- visualisation appropriate to conservation tasks;
- support processing appropriate to conservation tasks;
- simulate architectural and archaeological features within GIS;
- support the processing of data representing architectural and archaeological features within GIS, to provide new information; and
- augment the GIS with textural information and other information on the architectural entities in the prototype.

1.4 Methodology

Adopting the following methodology will complete the tasks.

The position of features will use 3-D Cartesian coordinates, measured by digital photogrammetry. Controlled terrestrial photographs will be acquired, of some test objects (including a castle ruin in north-west Scotland, the interior of an abbey in France, a façade of the Gilbert Scott Building of Glasgow University, the Hunter Memorial in Glasgow and a rock sculpture in Iran) using the Zeiss UMK 10/1318 (metric terrestrial camera whose images will be scanned) or appropriate digital cameras. These measurements must be shown to meet the accuracy requirements.

The various measurements traditionally taken off line drawings must also be possible in the A/AIS, and more so, potentially. A set of test measurements will be established and executed. The outcome will be evaluated against checks.

There are requirements in architecture and archaeology for line drawings, and specifications exist for these [Debevec *et al.*, 1996]. It must be investigated as to whether these can be produced in the A/AIS.

There may be other requirements for digital data, rectified photography, orthophotography and stereo photography in archaeology and architecture [Dallas, 1996]. These will be identified and the information system's ability to provide them investigated.

An aim of photogrammetric data acquisition and processing is to create a 3-D geometric object description, which is photo-realistic. The ability of the information system's CAD tools to achieve this with data imported from a terrestrial digital photogrammetric processing system must be investigated.

1.5 Thesis Structure

The thesis consists of seven chapters.

In Chapter 1, the investigations have been introduced. Terrestrial Photogrammetry is suggested as a source of the 3-D data, which can be used to model archaeological and architectural objects in an information system, appropriate for any necessary future renovation. The tools typically found in a GIS (e.g. CAD, measurement, visualisation, draughting) have also been identified as useful for the purpose.

The second chapter reviews three-dimensional measurements and concepts associated with the three-dimensional modelling of objects.

The third chapter reviews the implementation of some three-dimensional models.

Chapter Four reviews the tools supplied by existing photogrammetric, GIS and CAD approaches which may be useful to the modelling of cultural (architectural or archaeological) objects and details the particular role digital photogrammetry can play in the modelling of cultural objects.

Chapter Five reviews two investigations done by others and five investigations performed by the author where he worked beside architects and archaeologists in order to become familiar with their methods.

The sixth chapter reviews the implementation of an A/AIS in the light of the author's experiences.

Chapter seven concludes the thesis. Any relevant new directions to be explored are indicated.

The thesis ends with the references, bibliography and appendices.

2. Three Dimensional Models: Concepts

2.1 Introduction

This chapter considers three-dimensional (3-D) measurement tools, and 3-D objects and their 3-D modelling.

Geomaticians use a variety of techniques to obtain precise measurements. These are transformed into 3-D coordinates in the object space, often utilizing least squares adjustment, thus obtaining the best estimates of these coordinates and an indication of their quality. The coordinate data acquired will usually need to meet some specified standard, in terms of accuracy or precision.

If the data capture techniques being used are photogrammetric, which is the main thrust of the work reported in this thesis, then the quality of measurement depends on a number of factors:

- the quality of the camera calibration parameters;
- the resolution of the camera or film and photo scanner;
- the quality of the camera position determination; and,
- the quality with which photograph object positions can be determined.

For example, even if a point object appears in two photographs but (while clear in one) can only be approximately located in the other of the photographs, then the resulting 3-D coordinate will have low precision and may be inaccurately placed in 3-D space. If there are too many points located in this way, even if other points are located precisely, the whole 3-D model may become inaccurate.

Photogrammetrists also need to understand the limitations of the measurement processing selected, when addressing quality issues; careful measurement is not enough. For example, camera calibration reports can be used to improve accuracy; applying the principal point offset corrections, supplied in a calibration report, to photo coordinates enables a more correct implementation of the collinearity condition, which is the fundamental functional model (see Section 4.2.1 and Figure 5.1.3) that defines the mathematical relationship between measured photo-coordinates and derived object coordinates, and is vital to the application of photogrammetry. It is likely that detailed *a priori* understanding of each component of the measurement system and the regular calibration of equipment need to be incorporated into procedures if data are to have sufficient quality.

An understanding of how the objects of interest, appearing in the photographs and whose images are measured, are going to be modelled is very important. Models are ways of symbolising objects. For any computerised geometric model, there can be considered two methods for representing an object: implicit and explicit. The vector model, based on lines, represents the implicit whereas the raster model involves the explicit representation.

Lines are needed in CAD packages, such as AutoCAD, which utilize the vector approach. However Fouch [1988] stresses the importance of the point entity in AutoCAD; it is points' locations that are measured in photogrammetry. Several methods are available for entering a point into a package such as AutoCAD. Points are recorded by their x, y and z values. An object can be modelled in 3-D space by entering the 3-D coordinates of its vertices, when AutoCAD requests points. Many other CAD systems also use vector data structures, based on point primitives. It is from these points that lines or polygons can be constructed.

Considering lines or edges, these bound polygons forming surfaces from which three-dimensional (3-D) models can be developed. The edges of these polygons may be defined by straight lines connecting vertices, as polynomials to define the edges in CAD systems or given by separate equations in terms of independent variables - parametric variables.

A polynomial is an algebraic expression consisting of one or more summed terms, each term consisting of a constant and one or more variables (typically x,y or x,y,z in the case of geometric modelling) raised to integral powers. One way to determine the terms' constants in such a polynomial involves using edge vertices as control points.

A parametric form can represent a whole curve in situations where is not possible to do this by a formula of the form $y = f(x)$, because there may be more than one value of y corresponding to a given value of x. The parametric form can support the analysis of the geometric properties of a curve, such as determining its tangent and normal [Mortenson, 1997].

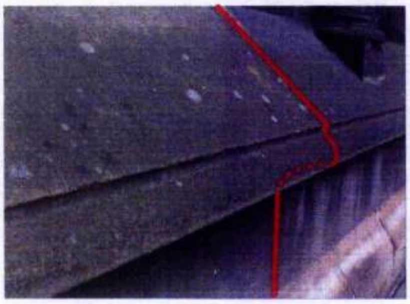
At present, in 3-D modelling the curves: Bézier, B-Spline and NURBS (Non-Uniform Rational B-Spline) which have natural extensions to surfaces, seem the most popular. The NURBS curve is a special form of a B-Spline curve and is the most general of these curves. The NURBS curve has become so widely used that it is almost an industry standard. "Non-uniform" and "rational" refer to specific mathematical properties of the curve. The curve is based on the ratio of two non-rational B-Spline basis functions, making it a vector-valued piecewise rational polynomial. NURBS curves are invariant under translation, rotation, scaling and perspective projection.

The curve-bounded segment of a surface is a surface patch; an assembly of patches is an effective way to represent a complex surface. The Bézier, B-Spline and NURBS bicubic patches are widely used forms in 3-D modelling.

If a curve does not appear, in part, (i.e. is occluded) in the photogrammetric system then it may be possible to compute part of the curve. However, if a curve changes direction in 3-D space *significantly*, it will have to be observed on three or more photographs [Eos Systems Inc., 2000]. Figure 2.1 shows a curve representing a feature's (a sloping and decorated window ledge) cross-section demonstrating this problem.

FIGURE 2.1

Curve (red line) whose shape cannot be correctly determined (i.e. at pecked occluded section) photogrammetrically unless more than two photos are taken



The Figure 2.1 feature will, with only two photos, be incompletely modelled; and the marked shape change will preclude it from being modelled mathematically. But, with more photos it can be completely modelled in 3-D. Each section of this type of complex curve needs to be in the field of view of at least two photographs. This can be achieved by selecting appropriate camera stations and camera rotations. Even closed NURBS curves or curves with 3-D object points at both ends, which appear to be completed, may have sections that are incomplete, for this reason.

From the foregoing, it can be seen that understanding geometric curves, surfaces and their components, as well as photogrammetry, is required in planning the photography for 3-D modelling based on photogrammetric input.

2.2 Three Dimensional (3-D) Coordinate Systems

In a Two-Dimensional (2-D) plane, the drawing is a collection of points, lines, arcs, curves or geometric entity types. To construct 3-D objects, requires 3-D (x, y, z) coordinates. Many computer graphics applications involve the display of 3-D objects. Until the segmentation of automatically gathered point clouds is perfected, the user, in terms of locating their vertices, will normally define these objects.

Output device coordinates are 2-D and present an x-y, y-z or x-z coordinate plane [Dewey, 1988]. But, a World Coordinate System (WCS) supplies 3-D information.

Using a WCS, any 3-D object can be displayed in an output device by disregarding one of the three (x, y and z) coordinates.

In architectural or archaeological (cultural) applications, and to support the photogrammetric measurement from a part of one façade, a set of well-distributed ground control points must be surveyed in a **local** coordinate system. A WCS is usually defined with the x and y coordinates in the horizontal plane and z in the vertical plane, but conventionally the x, y axes of a building's local coordinate system are approximately parallel to a selected façade of the object.

Ground control points (GCPs) on building façades are selected amongst targeted points or other easily identified natural points appearing in the images. The coordinates of the control points can be determined by a variety of surveying methods. If intersection is used, then measurements from, at least, two stations with, e.g., a 1" (4.8×10^{-6} rads) theodolite, are made and measurement of the base distance performed with a 1mm tape as accurately as possible (maximum error 2 mm, estimated SD 0.6mm). Likewise angles will be measured as accurately as possible (maximum error 9.6×10^{-6} rads, estimated SD 3.2×10^{-6} rads). Therefore, on the basis of a pre-analysis applying variance propagation the achieved precision of the GCPs can be assumed to be less than a millimetre for all three coordinate values. It should be mentioned that neither precision nor accuracy are the first concerns of this work, although once a working methodology is established these could be considered, and should reach acceptable standards.

3-D objects are constructed in a 3-D space, typically in a right-handed Cartesian coordinate system. Generally, the origin of a Cartesian Coordinate System (CCS) such as a WCS is at value (0,0,0), although false origins are also frequent in WCSs. On a screen display, the origin will appear at the bottom left corner of the data having positive coordinates, but in some systems, the origin is at the upper left corner. It is useful in an architectural or archaeological project to have a local coordinate system (LCS) and to ensure that the origin of the LCS is positioned to avoid (error causing) negative coordinates.

A scene is made up from a combination of simple geometric types. For computer drawing, any CAD system coordinates can be divided into device (e.g. screen) coordinates and local coordinates. The conversion between these two is commonly supported in CAD systems. The conversion from a local coordinate system to a World Coordinate System may not be supported by a CAD system, although in a GIS it should be.

2.3 Spatial Objects

As Star and Estes [1990] state, spatial objects can be divided into four categories; zero dimension (0-D), One-Dimension (1-D), Two-Dimension (2-D) and Three-Dimension (3-D) objects. To represent the geometric location of a point, a 0-D object is used. The straight line that connects two points is 1-D object. 2-D objects are areas with several different forms. One of the most important of these areas is a region, which is bounded by its bounding line segments. The 3-D objects employ three-dimensional regions. A solid modelling system represents a 3-D region. Solid modelling systems geometrically describe their objects by their location, shape and volumetric entities.

2.3.1 Three-dimensional (3-D) Points

The data collected for modelling a building often consists of individual 3-D points (0-D objects). These points are convenient for modelling the facets of a building. The first task of such modelling is to group the data to form facets (frames, façades, flat faces). The position of these facets can be defined by a listing of their vertices. Therefore, facets are polygons with a number of edges; many vertices on adjacent facets share the same coordinates.

In the AutoCAD environment, for example, there are facilities that can model a shape using points. The shape is often developed from a network of points upon which other geometric entities are constructed. These points may be point entities themselves, or implied points (relating to other entities or intersections). The centres of rotation for any shape are also points. The most important use of points is to indicate the locations of objects Fouch [1988].

2.3.2 Three-dimensional (3-D) Lines

A **specific straight** line can be defined by identifying two distinct points that the line passes through, or by giving one point that it passes through and also describing how "tilted" or rotated the line is – as in the equation of a straight line.

Linear equations are easy to recognise; they observe the following rules:

1. They have one (2-D lines) or two (3-D lines) dependent variables;
2. The variables (usually a combination of x,y or z) appear only to the first power;
3. The variables may be multiplied only by real number constants; and
4. Any real number term may be added or subtracted.

The graphs of linear equations are always straight lines. Equation $y = 2x - 1$ is an example of a graphing function producing a graph that is a straight line. This equation is one example of a general class ($y = a * x + b$) of equations called *linear equations in two variables.*

A familiar case of linear analysis requires solving a system of linear equations for two or three unknowns. For example determining whether or not a family of lines or planes has a common point of intersection – determining common y, z coordinates for intersecting lines given the x-coordinate. Assuming a redundant number of points, the usual method is least squares, which decreases (or minimises) the sum of the squares of the errors (or residuals or vertical distances off the line).

As stated in this chapter's introduction, geometry is usually created from polygons. The edges of these polygons can be straight lines connecting up the vertex coordinates. Although simple, the straight-line form of model seems particularly good at accurately representing features in space such as the edges of a 3-D structures and calculating sections, which intersect these lines. This form of model is geometric in origin and suited to CAD applications. Having the two ends points of a line, drawing a line on a paper is achieved in any CAD system, using the commands; *pen up/down* and *move*. Dewey [1988] suggests that the most basic concept in computer graphics such as *pen up / pen down* and *move* are approximations to hand drawing/sketching. Having the two end points of a line, for example, drawing this line on a paper commences with a pen up and move to the starting point and a pen down and move to the ending point.

An alternative to straight lines are **geometric curves** which can be represented in three ways; these are classified as follows:

- implicit curves,
- non-parametric curves, and
- polynomial curves

To explain, the mathematical representation of a unit circle (radius = 1) is considered. There is a need to define the x-y coordinate system within the drawing area of the circle. Since the distance between the centre of the circle $C(a, b)$ and a point $P(x, y)$ on the circle is r (radius), the relationship between these two coordinate variables can be given:

$$(x-a)^2+(y-b)^2-r^2=0 \qquad \textbf{(2.1)}$$

Equation (2.1) is in a form $f(x, y)=0$, called an *implicit equation* of a curve. Equation (2.1) can be changed into Equation (2.2) where it is said to be a *non-parametric equation*:

$$y=((r+x-a)(r-x+a))^{1/2}+2b \qquad \textbf{(2.2)}$$

If θ denotes the angle between the radius PC and the circle's horizontal-diameter as shown in Figure 2.2, then individual coordinate values become functions of θ. That is:

$x = r\cos\theta + a; \ y = r\sin\theta + b$ **(2.3)**

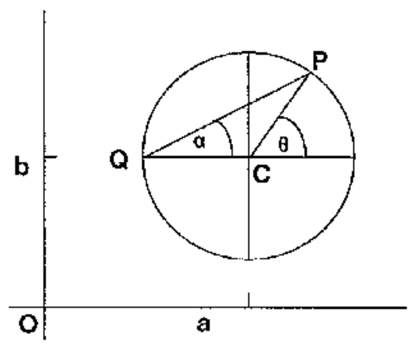
or

$\tan\theta = (y-b)/(x-a)$ **(2.4)**

where θ is a parameter of the curve (circle). Equations (2.3) or (2.4) are called the *parametric equations* of a circle (curve).

To consider a different parameter for the unit circle, the angle between a chord of this circle, PQ (Q is placed on the horizontal-diameter of the circle, as shown in the figure below, and the x-axis is α. Then (equation 2.5) is obtained:

Shows a Circle with its Centre at the Point $C(a, b)$



$\tan\alpha = (y - b) / (x - a + r)$ **(2.5)**

which can be re-stated as the general case:

$\tan\alpha = y / (x + r)$ **(2.6)**

From this equation and equation (2.1), other parametric equations of the unit circle are obtained:

$$x = x(t) = r(1-t^2)/(1+t^2); \qquad \textbf{(2.7)}$$
$$y = y(t) = 2rt/(1+t^2)$$

where $t = \tan\alpha$.

The above form is a *rational polynomial* (parametric) form, because individual equations are defined as ratios of polynomials in the parameter t. The process of obtaining a (rational) parametric representation from an implicit polynomial equation of curves or surfaces is called parameterisation. Supporting mathematical texts are listed in the bibliography (e.g. Waggenspack *et al.* [1987]).

As Choi [1991] determines, a space curve is conveniently represented in a parametric equation of the form: $x = x(t), \quad y = y(t), \quad z = z(t)$. For convenience, the following vector notation is used when describing a space curve in a 3-D Cartesian coordinate system: $r(t) = (x(t),\ y(t),\ z(t))$. With a parametric representation, a segment of a space curve is easily defined by specifying the range of the parameter.

Using a single implicit or explicit equation one cannot represent the segment of a space curve. Since an implicit equation of the form $f(x, y, z) = 0$ stands for a surface, there are two such equations needed to define the segment of a space curve. In this case, the space curve to be defined is in an intersection of two surfaces.

Polynomial Curves

In the previous section it was shown that for each space curve segment, different mathematical functions can be used as a curve model. Polynomial curves are widely used, as they are easier to work with and flexible enough to represent most curves in the architectural and archaeological domain. Polynomial curves can be used in representing a curve segment specified by its end conditions, two points and two tangents. Since these four vectors define the curve, it can be modelled by a cubic vector-valued polynomial function.

Cubic polynomial curves are used in ordinary curve modelling because a cubic polynomial is the minimum degree polynomial that provides enough flexibility for constructing a spatial curve. Some cubic polynomials are: the Ferguson curve; the Bézier curve; the uniform B-Spline curve; and the non-uniform B-Spline curve. A standard polynomial function is easy to define and efficient to evaluate. A vector-valued cubic polynomial function considered by Choi [1991] has the forms:

$$r(u) = (x(u), \quad y(u), \quad z(u)) = a + bu + cu^2 + du^3$$

or

$$r(u) = \begin{bmatrix} 1 & u & u^2 & u^3 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}$$

or

$$r(u) = UA, \text{ with } 0 \leq u \leq 1 \qquad \textbf{(2.8)}$$

In Equation (2.8), $U = \begin{bmatrix} 1 & u & u^2 & u^3 \end{bmatrix}$ and is called the basic power vector (a row matrix), and $A = \begin{bmatrix} a & b & c & d \end{bmatrix}^T$ is the coefficient vector (a column matrix).

Considering a vector-valued polynomial function r(**u**, v) whose degrees are cubic in both u and v with coefficients d_{ij} (for $u^i v^j$), then a bicubic polynomial patch can be defined as:

$$r(u, v) = \sum_{i=0}^{3} \sum_{j=0}^{3} d_{ij} u^i v^j \quad \text{with } 0 \leq u, v \leq 1 \qquad \textbf{(2.9)}$$

which can be expressed in a matrix form :

$$r(u, v) = U\ D\ V^T$$

$$where,\ U = \begin{bmatrix} 1 & u & u^2 & u^3 \end{bmatrix},$$

$$V = \begin{bmatrix} 1 & v & v^2 & v^3 \end{bmatrix},$$

and

$$D = \begin{bmatrix} d_{00} & d_{01} & d_{02} & d_{03} \\ d_{10} & d_{11} & d_{12} & d_{13} \\ d_{20} & d_{21} & d_{22} & d_{23} \\ d_{30} & d_{31} & d_{32} & d_{33} \end{bmatrix}$$

where D is the coefficient matrix.

A cubic function may be used in constructing a curve segment passing through four spatial data points (Ferguson function). In general, a degree n polynomial curve $r(u) = \sum_{i=0}^{n} a_i u^i$ can be used to fit (n+1) data points.

For segments, function-based representations are generally based on parametric polynomials, NURBS [Fisher and Wales, 1991]. These functions can structure points or primitive geometrical forms into a single exact 3-D model by the assembly of surface components. Transformations and analyses of such representations are rapid and efficient.

The process of data modelling begins with the identification of a real structure (greatly supported by practice and experience). This step is normally followed by measurement.

Observations of the measurements are usually made with reference to a 3-D coordinate system with acts as a geometrical frame. The measurement technology used may define the geometrical arrangement of the observed points on an architectural object's elements, for example a digital photogrammetric survey may generate a grid of measurements over the object.

Curve Fitting Methods

It is generally accepted that a curve can be generated by sweeping a point through space, a surface by sweeping a curve through space, and a solid by sweeping a surface through space. Just as has been done for space curves, for the spatial representation of surfaces (and solids), it is convenient to use vector-valued parametric functions.

2.4 Surfaces

Any physical object is bounded by its surfaces. According to Choi [1991], there are five ways of describing surfaces for drawing purposes [Choi, 1991]:

- surface primitives;
- mesh of curves;
- sweepings of cross sections;
- sets of 3-D points; and,
- blending surfaces.

This section summarises the basic concepts of surface representation. The mathematical equations describing a surface may be in implicit form, parametric form or non-parametric form.

2.4.1 Implicit Representation

As we supported some discussion of curves with a circle, so we will support the discussion of surfaces with a sphere.

The most basic definition of the surface of a sphere, as a set of points an equal distance of a radius r from the origin of 3-D space coordinates (x, y, z), is given by Equation (2.10):

$$x^2+y^2+z^2=r^2 \qquad \textbf{(2.10)}$$

If the expression on the left is less than r^2, then the point (x, y, z) is on the interior of the sphere and if greater than r^2 it is exterior the sphere.

2.4.2 Parametric Representation

As Choi [1991] states, in differential geometry a surface is defined as "the image of a sufficiently regular mapping of a set of points in a 2-D space for 3-D space", and it is expressed as:

$$r(u, v) = (x(u, v),\ \ y(u, v),\ \ z(u, v)) \qquad \textbf{(2.11)}$$

where u and v are parameters of the surface.

Returning to the unit sphere, one may parameterise the implicit Equation (2.11) by taking u and v as longitude and latitude, respectively.

$$r(u, v) = (\cos v \cos u,\ \ \cos v \sin u, \sin v) \qquad \textbf{(2.12)}$$

with $0 \le u \le 2\pi$ and $-\pi/2 \le v \le \pi/2$. As with the unit circle Equation (2.7), a different parameterisation using a rational polynomial form is possible. Such a parametric form is given by Mudur [1986] as:

$$x(u,v)=(1-u^2)(1-v^2)/(1+u^2)(1+v^2);$$
$$y(u,v)= 2u(1-v^2)/(1+u^2)(1+v^2);$$
$$z(u,v)=2v(1+u^2)/(1+u^2)(1+v^2).$$

2.4.3 Non-parametric Representation

If a surface's domain is taken to be the x-y plane of a Cartesian coordinate system, the parametric form (2.11) becomes a *non-parametric equation* (Note $u \equiv x$, $v \equiv y$):

$$r(u, v) = (u, v, z(u, v)) \qquad \text{or} \qquad z = z(x, y) \qquad \textbf{(2.13)}$$

If the surface is defined on a bounded domain, it is called a *surface patch* or simply patch. An assembly of patches with prescribed interpatch continuity conditions is called a *composite surface* [Qiulin and Davies, 1987].

2.5 Geometric Models

The requirements for any computer modelling of an object, are: data, algorithms and structures.

The data are the most basic elements in the modelling of an object and consist of numerical values, characters, instructions, or any other representation of spatial and non-spatial attributes, defined in a formal language.

Algorithms indicate how the data should be manipulated.

Structure indicates how the data are organised. Two alternative approaches that are used to implement spatial data structures in the computer are geometric modelling and the raster approach. In geospatial sciences the terms: vector and raster are more common. This section details the vector (geometric modelling) approach and section 2.6 the raster approach.

Geometric models represent 3-D solid entities by describing, mathematically, collections of points, lines, faces and solids (often with appropriate rendering). Geometric modelling strives to recreate the structure of an individual entity without necessarily needing to consider that entity's relationship with other entities or other non-spatial attributes of the entity. However in the applications of concern to this work these relationships and attributes are important.

Geometric modelling is becoming increasingly important in building approval and design. The application of geometric modelling for impact assessment purposes, for example, is both to support approval of and to be a part of the eventual design process. For example, rendering, an important component of modelling, mimics the physical behaviour of an entity's components in an effort to establish the final appearance of a design.

With reference to geometric modelling for architectural and archaeological applications, there are several steps to be followed. The first step is only the 2-D representation of an object; such as taking a photograph. The subsequent steps involve the 3-D modelling of an entity. This modelling is first based on, for example, CAD. Subsequently, the model may be enhanced with information making it possible to match the architectural and archaeological sites and any relevant topological information. Other useful extra information items can be attached to an object's geometric representation. These are attributes. For example, to associate surfaces in a model with a particular part of the model (such as the interior, an edge or the north-face) the simplest attribute is colour and all modelling tools allow this. After colour, the next most useful attribute is a text string, especially if the modeller does not place restrictions on its length. Indeed, given arbitrary-length text strings it is possible to encode anything as an attribute (including colour), but this is not always as efficient as storing things less flexibly. Another very common attribute is a pointer. This allows the address of any data containing relevant information to be attached to the model, as a further attribute. These examples of topological information and attribution show how the geometric model migrates to a vector model as supported in a GIS.

In 3-D GIS, both vector and raster data are often utilised as required. For example although the original source data may be a digital photograph, or perhaps a digitised photograph, these raster data will be processed to provide (e.g.) edges of faces (i.e. vector data) and also fragments of the photographs to be used for rendering (i.e. raster data).

Taking Physics' definition of a vector as having magnitude and direction, in GIS lines defined by a magnitude and a direction (achieved by recording strings of consecutive vertices) contribute to forming vector models. The vector model represents each feature as a row in a table, and feature shapes are defined by *x,y* locations in space. The table (or linked tables) can also record relationships between entities (topology) or attributes of individual entities.

Generally, vector models can support architectural applications which involve line drawings. There may be considered to be four different types of 3-D vector representation schemes in graphics models [Debevec *et al.*, 1996], which are:

- 3-D wire-frame models;
- surface models;
- boundary representation; and,
- solid models.

These 3-D vector models are considered in the following sections 2.5.1, 2.5.2, 2.5.3, and 2.5.4.

In the conservation of cultural objects, each of the above has its own particular application. Which is to be used depends on the ability of the method to model certain geometric structures effectively [Dewey 1988]. These methods have been developed for 3-D modelling and involve the representation of geometry as a collection of lines (or polylines) and other curves, surfaces or solids in space. 3-D vector models are constructed in 3-D space, typically in a right-handed Cartesian coordinate system.

For reference, AutoCAD supports the following:

- Wire Frame Modelling
- 3-D Face Modelling (3-D Surface Modelling, 3-D Mesh, 3-D Patch, Revolved Surface, Tabulated Surface, Ruled Surface, Edge Surface)

- Boundary Representation Modelling
- Solid Modelling

2.5.1 3-D Wire-frame Models

Most of the early 3-D systems used wire-frame models. In 3-D wire-frame models, the geometry is defined as a series of points with straight lines joining them, representing the edges of the object [Leigh 1991; Onwubiko 1989; Chiyokura 1988].

A wire-frame model is stored very simply in a computer. The 3-D wire-frame scheme is relatively straightforward to use and is the most economical of the 3-D schemes in terms of computer time and memory requirements [Hsu and Sinha, 1992]. The coordinates (x, *y* and *z* values) of each point are stored in a table. This is quite adequate to represent a shape, position and orientation of an object, but wire-frame models include no information about surfaces. This means that a wire-frame model is not very informative about surfaces, and can be ambiguous when presenting the surface of, or calculating the surface area or volume of an object.

2.5.2 Surface Models

To overcome the ambiguities of wire-frame models, surface modelling has been suggested. In general, surface models, as Chiyokura [1988] describes, involve a series of geometric entities, with each entity formed from a single face (facet). Therefore, tables of edges and points plus a table of faces represent a surface model. Surface modelling is suited to situations when interior details are not important [Leigh, 1991].

Surface models are constructed from edges and curves on the surface and so surface models are often developed from wire-frame representations or mixed with them. A display of 3-D curved lines and surfaces can be generated from an input set of mathematical functions defining the objects or from a set of data points which are specified by the user. Woodwark (1986) identified a need for the representation of curves that overcome the limitations of the explicit and implicit forms.

Parametric surface models are important design tools in the computer environment. They are widely used in constructing and reconstructing a composite surface from a set of 3-D points. Mortenson [1990] has shown Bézier surfaces are a class of parametric surfaces that have been particularly useful in the area of geometric modelling and computer graphics.

3-D Polygonal Surface Meshes

3-D polygons are locationally specified by a list of 3-D vertices. According to Sarter *et al.*, [1994] conventionally vertices proceed in a counter-clockwise direction when the viewer is in front of the polygon (and outside the object); the last vertex must be connected to the first point; there is no limitation for the number of vertices, but self-intersecting polygons should be avoided. In order to implement this idea and create a 3-D polygon, sorting 3-D points is needed.

A polygon representation can define the surfaces features of a polyhedron object. But for other objects, surfaces are tessellated to produce a polygon-mesh approximation. For example, the surface of a cylinder is presented as a polygon-mesh. Such, in effect, dense wire-frame representations are common in design and solid modelling applications, since the mesh outline can be displayed quickly to give a general indication of the surface structure. Kalameja [1995] has noted that interpolating shading patterns across the polygon surfaces, to eliminate or reduce the presence of polygon edge boundaries, produces realistic renderings. Moreover, the polygon-mesh approximation to a curved surface can be improved by dividing the surface into smaller and smaller polygon façades.

As mentioned earlier, various mathematical functions defining the objects can be used to display 3-D curved lines and surfaces. Spline representations are examples of these curves and surfaces. For surfaces, a functional description is often tessellated to produce a polygon-mesh approximation to the surface. Usually, this is done with triangular polygon patches to ensure that all vertices of any polygon are in one plane, as polygons specified with four or more vertices may not have all vertices in a single plane.

Division of Surface into Planes

The most elementary of the surface models are flat planes, which may be defined between two straight lines, through three points or through a line and a point [Thomas, 1988]. But the basis of the general definition of a surface is a curve defined in a given plane. This can be swept along another curve defined in another plane. It is the definition of the sweeping and swept curves which determine the characteristics of the surface patch. Surface models include the widely used natural quadric surfaces such as plane, cylinder, cone and sphere, together with the torus (doughnut), as a special case. With polygonal models, additional polygons are easily created where they are needed, but an extremely large number of data points may be required to represent a smooth surface.

3-D faces in computer systems are modelled as 3-D polygonal surface meshes which may be constructed as planar (flat) surfaces or as non-planar surfaces. Each 3-D surface mesh is either a triangle or a quadrilateral.

Surface models contain neither information about connections between surfaces nor about which part of an object is solid. A surface model is a set of faces, and as such is ambiguous when, for example, determining the volume of an object; if information is added about connectivity between surfaces and in addition the solid side of any face is identified, then these form the elements of the boundary representation, discussed in the next section.

2.5.3 Boundary Representation

Representing an object by its boundaries can be referred to as Boundary Representation (B-rep) [Weiler, 1985]. The bounding surface of a solid object separates the inside from the outside of the solid. The bounding surface of a solid is the primary interface between the solid and the surrounding environment. It is computationally convenient to segment the boundary surface of a solid object into facets (or planar faces or patches) with each facet in turn bounded by a set of edges and vertices.

The B-rep of an object is a collection of both geometric entities (such as vertices, edges and faces) and the topological relationships between the entities. In conventional CAD systems, the use of non-planar faces is usually restricted to the quadrics such as cones, cylinders, spheres, etc., but CAD systems are now emerging which use a variety of formats to represent e.g. sculptured torsos.

The simplest form of B-rep model is one that represents all faces as flat planes. A curved surface such as cylinder is represented in such a model as a series of flat plane faces that approximate the surface.

In B-rep, it is essential to check the topological consistency of a model, in particular that there are not any extra or missing faces or connections [Woodwark, 1986]. Topological consistency is achieved by using a data structure in which faces are linked (with the appropriate adjacency relationships) to their boundary vertices in a uniform structure. To do this B-rep involves five tables; vertex coordinates, edge/vertex, face/edge, object/face and normal vectors. The coordinates of each vertex are stored in the first table called the *vertex coordinates* table. The vertices at the ends of each edge can be accumulated in the *edge/vertex* second table, storing the vertex identifiers associated with each edge. The relationships between faces and edges are stored in the third table called *face/edge* table, examples being the edge identifiers associated with each face. The relationships between modelled object and face identifiers are stored in an *object/face* (fourth) table. The final table stores the normal vectors of faces and is called the *normal vectors* table.

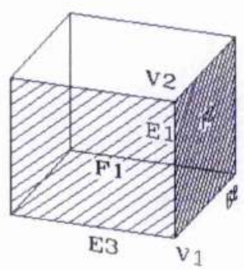
The most commonly used Boundary representation for a 3-D graphics object is a set of surface polygons that enclose the object's interior. Many graphics systems store all object descriptions as sets of surface polygons. This simplifies and speeds up the surface rendering and display of objects, since all surfaces can be described merely with linear equations [Thomas and Huggett, 1980].

In B-rep, planar faces are represented by their bounding edges. However, curved (i.e. non-planar) faces require more information. For example, a region with a Bézier surface can be defined by its geometric coefficients; that is the actual curved face is defined by its constituent polyhedra [Risler, 1992]. But, one of the most common methods is the B-Spline representation, which is a category of surfaces employing parametric polynomials.

Figure 2.2 shows an example of the topological information B-rep supports. Edges run between vertices and connect faces. For instance, edge E1 runs between vertices V1 and V2, and connect faces F1 and F2. Vertices connect edges; for example vertex V1 is connected to edges E1, E2 and E3. The advantage of this modelling is that a solid can be represented as a closed 3-D space. Because boundary representations include topological information, it must be possible to distinguish the inside of the surface of an object from the outside.

FIGURE 2.2

Boundary Representation



B-rep achieves this by sweeping the model space with either a line that rotates around an axis or a wire-frame; in either case the enclosed spaces are identified. Thus, as Chiyokura [1988] states, the great advantage of B-rep is that it is essentially a further continuation of the process, which generates a wire-frame model first and then its surface cladding.

The B-rep method offers improved performance in display generation and more flexibility in the forms that may be modelled. Thus, a B-rep system can be used with a wide variety of objects to generate 3-D models, particularly if there is no need to go beyond the surface modelling stage. For example, the object shown in Figure 2.2 can be modelled using a wire-frame method. The border of each plane of this 3-D object can be achieved first using a standard script file. For example standard script files in AutoCAD (*3dpoly.scr*) contain a list of all the planes of an object and for each of these planes all vertices are stored as 3-D coordinates. Then, the planes of objects can be formed as a 3-D polygonal surface meshes using the '*3dface*' command of AutoCAD.

The benefits (+) and drawbacks (-) of B-rep are as follows:

- Making pictures is easy (+)
- Calculating surface area is easy (+)
- Calculating volume and mass is difficult (-)
- Problems exist with numerical accuracy (-)
- Widely used (+)
- The data structures use much memory (-)
- There have been many technical developments (+)
- Input can be messy without extra software (-)

2.5.4 Solid Models

Solid models use 3-D data and are created by forming sets of triangles. These triangles may overlap when viewed in two dimensions, but do not overlap or intersect when the third dimension is considered. The triangles in a solid model may completely enclose a structure. Solid models use triangles to link polygonal shapes together to define a solid object or a void. Solid models are based on the same principles as using Triangulated Irregular Network Surface Models (TIN DSM) to define a surface. A TIN DSM is a computer surface model of an object supporting tasks such as estimating slope gradient, aspect, curvature, etc. in GIS. The resulting shapes may be used for:

- Visualisation;
- Volume and mass calculations;
- Extraction of slices in any orientation;
- Surface descriptors; and
- Intersection with data from the geometry database.

Triangles are formed by connecting groups of three data points together by taking their spatial location on, e.g. the height above the x-y plane into consideration. Solid modelling supported by a CAD system is extremely useful for the representation of architecture and structures, both for modelling and design. This applies in particular to items having complex shape and volume.

3-D representations supply the virtual image of the object under observation, and this can be used for a number of applications. For instance, it is possible to obtain orthogonal and perspective views, as well as sectional views, calculation of volumes, areas, other dimensions, curvature, higher order geometric variables and verification of the viability of components' assemblies, from 3D representations.

Moreover, solid modelling is applicable in Geomatics, for the representation of built areas and for archaeological or other cultural surveys. Surveyed points usually represent the land with a pre-established density, and the land is modelled by means of calculations that interpolate the surveyed data. The representation obtained can then be processed again in order to carry out morphological and environmental analysis - such as curvature, cleavage analysis, slope exposure and the reconstruction of archaeological excavations.

The two principal methods for solid models representation are B-rep and Constructive Solid Geometry (CSG). B-rep can store data through describing vertices, edges and faces and was described in 2.5.3. As the B-rep of a solid model carries information about faces, edges and vertices and their adjacencies and no information about interior relationships (e.g. centre of mass and volume) there is no information for producing the solid if restarting from the beginning is needed. This is a drawback for B-rep.

CSG stores the parts of an object as a tree, where the leaves of the tree are the primitives and the nodes are the Boolean operations. Dewey [1988] has concluded that many systems have recently been mixtures of two techniques, using both CSG and B-rep.

As well as CSG, there are two other solid modelling systems: primitive instancing and sweep representation, discussed in this section.

Constructive Solid Geometry (CSG)

CSG stores the arrangement of basic shapes and geometric operations. Unlike B-rep, CSG methods record how the solid is produced (from a few primitives with Boolean Operations, e.g. union, intersection and difference), but an evaluation of the sequence of appropriate Boolean Operations has to be presented before determining anything about the real shape. Every solid constructed using the CSG technique has a corresponding CSG expression, which in turn has an associated CSG tree. The expression of the CSG tree is one representation of the final design. This means that the same solid may have different CSG expressions/trees.

The CSG model is stored in a tree with operators at the internal nodes and primitives at the leaves. As such, the shape of the object and the process of building the object are implicitly described in a single data structure. Thus, a CSG solid can be written as a set of equations and can also be considered a design methodology.

Constructive Solid Geometry (or CSG) is a term for modelling that defines complex solids with an initial set of 3-D objects (primitives) such as blocks, pyramids, cylinders, cones, spheres as well as closed Spline surfaces. The primitives can be provided by the CSG package as menu selections or the primitives themselves could be formed using sweep methods, spline constructions or other modelling procedures. In more representative engineering components, hundreds of primitives may be required, making the input process potentially protracted. Boolean operations are used to execute the composition. It is possible to consider the CSG as a generalisation of cell decomposition. In such a representation, the components are joined using a 'gluing' operation. In other words, a limited form of the union operation is performed where components are joined at only perfectly matched faces. But CSG operations are more versatile, since boundaries of joined components (primitives) need not match and interiors need not be disjointed.

Furthermore, CSG uses all the standard Boolean operations: *union*, *subtraction* and *intersection*. In *union* (joining the objects), any surfaces that are internal to the result are discarded. This is because if a section goes through a unioned object (similar to inserting a screw into a piece of wood) it cuts out all bits that made up the original parts and they will not reappear. *Subtraction* uses one solid to cut away part of another solid. *Intersection* operates similarly to the union order. Two (or more) objects are combined such that the resulting solid is the shape of the space in which they intersected. Nevertheless, Boolean operations are quite complex and are expensive to carry out because they require numerous comparisons to be made.

Primitive Instancing

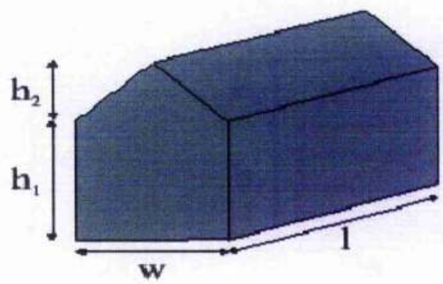
Primitive instancing represents solids formed by a set of pre-defined object types. Each object type is represented by a small set of parameters, and individual instances are created by selecting a model type, providing the new instance and applying a rigid motion (a translation and a rotation in 3-D space) to the primitive. In the terminology of geometric modelling a family is called a *primitive* and each member of it an *instance*.

It is the concept of primitive instancing to provide solid 3-D primitives that are described by a set of parameters reflecting the object dimensions. This method of 3-D representation is unambiguous, easy to validate, concise, simple to use and Boolean operations are computationally simple. For the object types contained in the primitive database, modelling becomes very easy and efficient. That is why primitive instancing is supported by many CAD and modelling systems as an assisting technique, even though the modelling system itself is based on other representations [Mantyla, 1988].

Figure 2.3 shows a simple building primitive described by its length (l), width (w), gutter height (h_1) and roof height (h_2). Conditions can be imposed on the parameters in order to achieve validity of all the models, which can be created by the variation of the parameters. For example, none of the parameters of the primitive in this figure may become negative or zero and they cannot operate with Boolean operations, e.g. no operations for the combinations of instances are possible [Suveg and Vosselman, 2000].

FIGURE 2.3

A Primitive Shape Described by the Parameter Vector $\mathbf{P} = (l, w, h_1, h_2)^T$



Sweep Representation

Sweep representation (called *generalised cone representation* by Chiyokura [1988]) describes an object by sweeping a determined area or volume along a defined direction. A sweep representation creates a 3-D object by means of a 2-D shape. An object creates by moving the 2-D representation through 3-D space denoting the movement as *sweep representation* [Hoffman, 1989]. There are three types of sweep representation: general sweeps, rotational sweeps and volume sweeps. Requicha [1980] reported that the mathematics of the general sweeps representation is unknown, because the intersection point sets cannot be calculated in all cases and it is thus likely to represent the detail in 3-D space, insufficiently. Thus, this kind of sweep representation is not used

More complex objects can be modelled by varying the size of the swept profile as it is swept along the curve, e.g. a seashell could be modelled by sweeping a steadily increasing diameter circle along a spiral curve. However, there can be difficulties caused by surfaces self-intersecting when these more advanced techniques are used [Miller *et al.*, 1991].

2.6 Raster Models

Raster data models are constructed from aligned cells. The positions of the cells in the horizontal and vertical directions are stored within the columns and rows of the array respectively. The rectangular array of cells (pixels) that is produced (such as on a raster display device) is called the raster. The distances between cells in the raster are (usually) constant in both the row and column directions; in this case, the cells in the raster are square and therefore, to store the data on a computer in a 2-D array is reasonable.

Raster data structures are usually based on the decomposition of a plane. In raster-based systems for representing spatial data, the ability to specify a location in space is limited by the size of the raster elements, since there is no facility to know about different locations within a raster cell.

2.6.1 Hierarchical Decomposition

Decomposition representation generates a hierarchical decomposition tree. In this context, a tree is a collection of elements where an element points to its parent as well as to its children. A tree will be called a hierarchical tree if the children of an element are associated with their parent in some particular relationship. The space can be divided by a recursion technique, which calls itself until a terminal element is achieved. Hierarchical decomposition representation, which represents solid objects by the connection of a set of cells, can be called cell decomposition. The hierarchical tree approach is a powerful technique solving many problems in geometric modelling systems and computer graphics [Requicha, 1980].

When an object has curved boundaries, the accuracy of the model depends on the size of the elements. Therefore, this method has a drawback, which is that it requires a large amount of memory for storing the elements' data. Another disadvantage of this model is that there are some difficulties to do with the lack of explicit representation for the adjacency between the cells in the hierarchy [Brunet, Juan and Navazo, 1989].

Usually no conditions are imposed on the neighbourhoods of points with respect to neighbouring cells. While the corresponding topology can be computed in principle, it may not be an attribute of the hierarchy itself, which implies the need for additional data structures and algorithms [Staib and Duncan, 1992]. For example, it is not immediately clear how to define, compute, and represent the boundary of a solid represented by this method. Perhaps, because the boundary of a solid is unique, it is possible to invoke additional conditions (e.g., smoothing, connecting, orientation, etc.) in order to define and construct the unique activities relating to the decomposition of the boundary.

One of the known existing unambiguous 3-D representations of the hierarchical decomposition method is spatial occupancy enumeration. This technique models any physical object as a number of equal sized cubes, some occupied others unoccupied, and is considered next.

2.6.2 Spatial Occupancy Enumeration

Spatial occupancy enumeration (SOE) is a technique to represent a solid object by the association of a group of primary volume elements or voxels. An object is represented by a list of the cubical disjoint spatial cells, which it occupies. There are two cell types: full cells inside the object; and, empty cells outside the object. All the cells are cubes of equal size [Bakalash and Kaufman 1989]. Davies and Yarwood [1986] and Brunet [1992] state that the primitive cells are adjacent (connected) but do not intersect. Kavouras [1992] proposes that SOE is a particular form of CSG.

When a large number of cells are occupied inside an object, a large amount of computer memory is required to represent the model. One of the best-known memory saving techniques for SOE is the octree (from: octal tree) [Kaufman *et al.*, 1993]. This is a solid modelling method in which arbitrary objects are represented at a specified resolution in one-to-eight hierarchical trees. Octree representation is thus a hierarchical form of SOE. An octree is a data structure which can define a shape in 3-D. An octree is a tree that codes the recursive subdivision process of a finite cube called the 'universe'. The 'universe' is divided into eight cubes of equal size. Then where more structure is needed, within a cube, it can be further divided into eight smaller cubes and so on, recursively. A tree can represent this where each node has either eight or no children [Rogers and Adams, 1990].

Thus a 3-D entity could be modelled by dividing the world into small cubes, the position of each cube could be represented by Cartesian coordinates (x, y and z) and if each cube was small enough then it could be considered to contain only one type of matter coded in some way. This would require an enormous array of data to hold a reasonable representation of an entity, because a large mass of homogenous matter would require just as much data as the very intricate parts of its outer structure, except that the 'childless' cells can be exploited. This might be an inefficient way to model the world; lots of details in the parts that need it are stored, holding this information in an octree, without wasting memory where it is not needed. Voxels allow fast rendering of independent shapes, that is rendering using customised voxel rendering routines without the use of polygon drawing. More details about octree representation are given in the next Chapter.

2.7 Advantages and Disadvantages of Vector and Raster Techniques

Raster data models are compatible with modern high-speed graphic input and output devices. In addition, the refresh process is independent of the complexity of the data [Houlding, 1992].

Regarding topological representation, in the raster approach, pixels are individually located but also have, usually, only one attribute value. In the vector representation, points are similar to pixels but they cannot represent any area. Lines and areas are sets of interconnected coordinated points that can be linked to a large number of attributes.

TABLE 2.1

The Relative Performance of Raster and Vector Structures

Spatial Structure	Function	Raster	Vector
Visualisation	Translation	Slower	Faster
	Rotation	Slower	Faster
	Scaling	Slower	Faster
	Reflection	Slower	Faster
Transformation	Shear	Slower	Faster
	Volume	Faster	Slower
Characterisation	Surface Area	Fast	Faster
	Centre of Mass	Faster	Slower
Inter-Relationship	Separation	Fast	Faster
	Adjacency	Fast	Faster
	Orientation	Slower	Faster
Modelling	Building	Faster	Slower

The disadvantage of the raster technique compared to the vector technique arises from this lack of 'connectedness' information, although algorithms to determine in which region a pixel lies, exist [e.g. Abel and Wilson, 1990]. Doing polygon overlay involves simpler algorithms than the corresponding algorithms for the vector format data. This is an advantage for the raster data model and a disadvantage of the vector data model. Table 2.1 gives an indication of the relative performance of raster and vector data structures [Raper, 1992]. This table compares the effect of the use of vector and raster spatial structures on 3-D spatial functions' speeds.

2.8 Summary

This chapter has presented some theoretical concepts, enabling an understanding of the relationship between captured data (i.e. point coordinates) and object representation in a spatial database (i.e., 3-D objects).

For the cultural applications, which have prompted this work, three-dimensional visualisation and the exporting of a shape needs to be completely developed in an information system. If a shape does not appear to be truly visualised in 3-D or exportable (e.g. the object cannot be rotated and 3-D object points cannot be extracted) then it means that the requirements for 3-D modelling may not have been met. This means it may not be possible to analyse the object's shape (e.g. slope, curvature, surface area, surface texture and dimensions in all directions). For example, NURBS curves may seem to be complete but may have sections that are inaccurate or even missing. It is the responsibility of the geomatician (and most likely the photogrammetrist) to be familiar with and even explain or provide advice on the geometric entities and their relationships with a 3-D shape, in order for the data to be captured adequately. In a system designed for the management and documentation of cultural monuments it may be archaeological or architectural specialists who are tasked with the job of data capture. Involved Geomaticians must give consideration as to the advice they provide to guide these archaeological or architectural specialists in their task.

All geometric modelling methods have two common features. The first one is the composition into cells, which can either be 3-D primitives in a CAD system or 2-D cells. The second common feature is the existence of links between these cells.

Considering the composition techniques, the three main representations used for the 3-D modelling of geometry in CAD systems are: wire-frame, surface modelling and solid modelling; which can be considered vector models. Wire-frame models are long established, but are limited in the way they can represent archaeological and architectural features. Surface models include widely used surfaces such as planes, cylinders, cones and spheres. Boundary representation (B-rep) is an extension of the surface representation scheme into solid modelling. The last expansion of the composition technique is constructive solid geometry.

Considering raster decomposition techniques, this chapter has considered hierarchical decomposition and spatial occupancy enumeration.

As the data gathering method advocated here (photogrammetry) can capture irregular points on the surface of objects of interest boundary-representations (B-rep) seems, at this point to be the most appropriate form of modelling.

The next chapter examines the implementation of the concepts presented in this chapter.

3. Three Dimensional Models: Implementation

3.1 Introduction

Computer graphics and the three-dimensional digital surface modelling of an object, as already mentioned, require three different components. These are: data, algorithms and structure.

Data, the most basic, can consist of several sub-components: digital imagery (digital numbers, DNs), characters, instructions or any other defined representation of spatial and non-spatial attributes. The digital imagery can be obtained with sensor-firmed cameras (or imagers) or film-based cameras and digitisation.

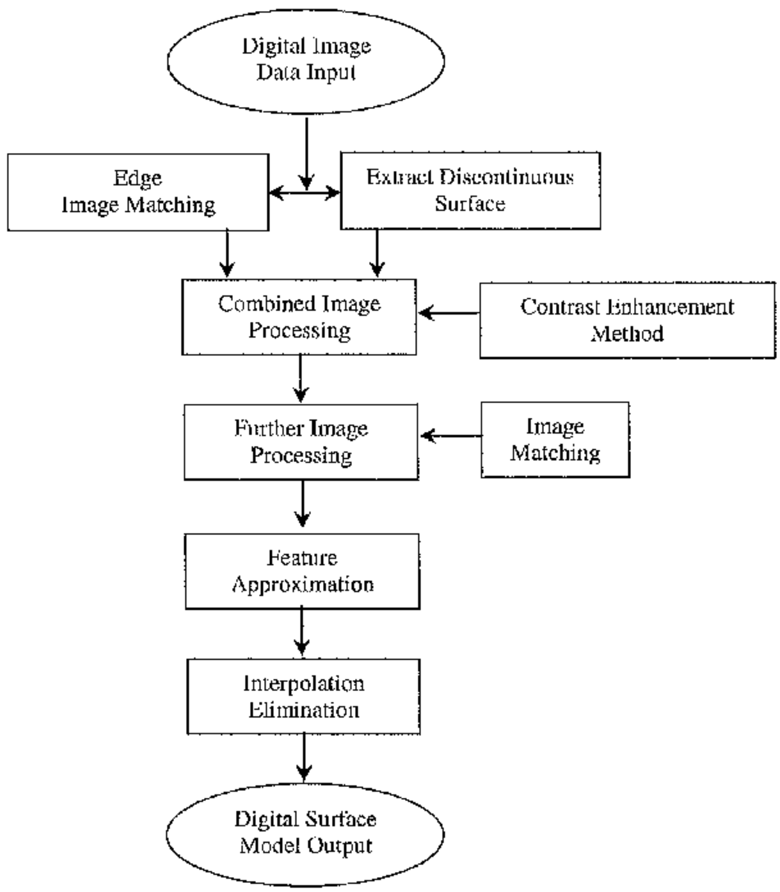
Algorithms indicate how the data are to be processed (including the names of any well established mathematical tools which have been identified as to be used). For example one of the algorithms used in this area of work is feature extraction and can be taken as an example. This can begin with approximate positions and processes iteratively to find the location of each edge, then 3-D vertices, with error minimized. The main processing steps of the feature extraction algorithm are as follows:

1. obtain approximate linear feature positions;
2. detect edges;
3. improve linear feature positions;
3. fit straight lines to linear feature positions; and
4. compute feature vertices.

Another example algorithm, is that to create a 3-D surface model from the photographs of a required cultural object. Figure 3.1 shows a flowchart of this 3-D surface modelling algorithm. Data input consists of the digital image, and also ground control points, approximate feature boundaries and other image data. Data output consists of a digital surface model of a selected object. This output can be used for other types of representation, such as octree representation (as will be discussed).

FIGURE 3.1

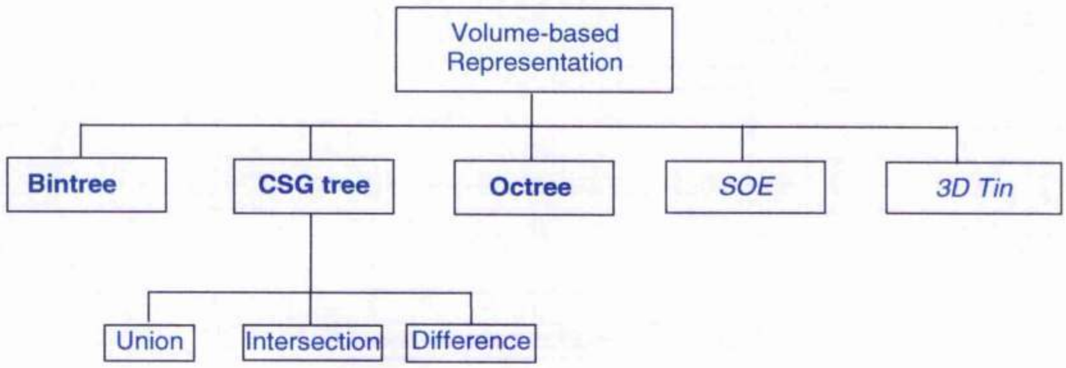
An Algorithm for the Creation of an Object's Digital Surface Model



Structure controls data organisation. There are, for example, several ways of structuring *non-spatial* data. Burrough [1986] reported the hierarchical, network and relational data structures as popular structuring methods for non-spatial data. But, more importantly for this work, as indicated in Chapter 2 there are several approaches for implementing *spatial* data structure in spatial information systems. These can be classified in different ways: wire-frame/surface/B-rep/solid; surface based/volume based; raster/vector, etc. Within these classes are some *specific* spatial data structures. The following sections review the implementation of some of these specific well established spatial data structures. These include linked list structures (Section 3.2) and volume based structures (Sections 3.3, 3.4, 3.5). The selection is not complete, for example Figure 3.2 summarises several volume-based data structures, but in this chapter the implementation of tree structures: Bintree, CSG Tree and Octree, are examined. Figure 3.2 also indicates the Boolean operations which can be performed within CSG Tree structures to represent objects.

Figure 3.2

Volume-Based Representations



3.2 Linked List Structures

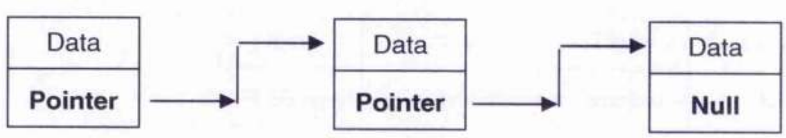
Linked lists are a classical data structure [Hahn, 1994]. A linked list is a collection of nodes, in which each node contains a data element and a pointer to the next node.

Setting one object's pointers to other objects forms linked data structures. These pointers link the separate objects into a single data structure. Feilel [1990] maintains there are two kinds of linked list: the *singly linked list* and *doubly linked list*.

A singly linked list contains a link to the next data item but a doubly linked list contains links to both the next and previous data item in the list. Figure 3.3 shows a singly linked list.

FIGURE 3.3

A Singly Linked List



A structure that contains a data element and a pointer to the next node can be created, in a high level programming language, by:

```
struct list {
        int  value;
        struct list  *next;
};
```

This defines a new data structure called a *list*, which contains two members. The first is an integer called *value*. The second is called *next*, which is a pointer to another list structure (or node). Suppose that two declared structures are the same type as list, e.g.,

```
struct list  n1, n2;
```

The pointer of structure *n1* may be set to point to the *n2* structure, e.g.

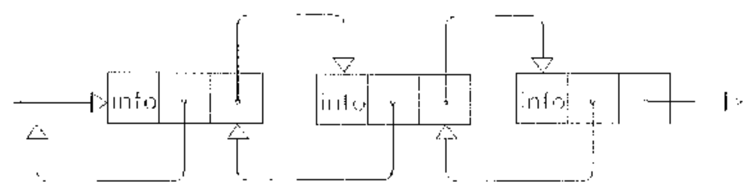
```
n1.next = &n2;
```

This creates a link between the two structures.

In a doubly linked list, each data item (or list structure, or node) points to both children and parent nodes. Using doubly linked lists makes it easier to search both forwards and backwards. For each data item, there is a pointer to a predecessor and another to a successor. Figure 3.4 displays a doubly linked list with three data items or nodes.

FIGURE 3.4

A Doubly Linked List



A singly linked list has many limitations [Watt and Brown, 2001]. For example, when traversing a link and reaching a data item, coming back to the former item is impossible. To reach a previous data item, the linked list must be traversed again from the first data item to the target. Therefore, when movement in either direction is needed, a doubly linked list is advantageous.

Using a linked list permits access to storage from a random starting point, because each piece of information carries with it a link to the next data item in the chain. One of the main advantages of using a linked list is that it allows the creation of arrays of unknown size in memory. Geospatial data sets can be distinguished from other data sets by allowing unknown or unpredictable size, thus the advantages of linked lists is obvious. But, using linked lists has inherent problems because whenever data modifications are implemented, in order to re-establish links the processing has to start from the beginning of the relevant entity, leading to inefficiencies.

3.3 Tree Data Structures

In comparison to linked lists, tree data structures (a subset of the class volume based data structures, see Figure 3.2) are defined by a finite number of elements called nodes. A tree is a collection of nodes in which each node can point to more than one other element. Arrays and linked list data structures are linear in nature but trees are non-linear data structures used to represent data having a hierarchical relationship. The relationships among the elements of an object can be represented as a special kind of graph known as a tree. The tree has one distinguishable node called the root. This is the anchoring node for the entire tree. Except for this node, each node in a tree has a parent node and each node has many child nodes. A node without a child is called leaf node or terminal node. Each node except the last node contains a pointer to the next node

Data structures such as linked lists and trees are sequential access structures. This means that it is necessary to go through nodes in order to reach a target node. To reach a node near the end of a list or near the bottom of a tree, it will be necessary to go through more nodes than when the required node is near the beginning of the list or the top of the tree.

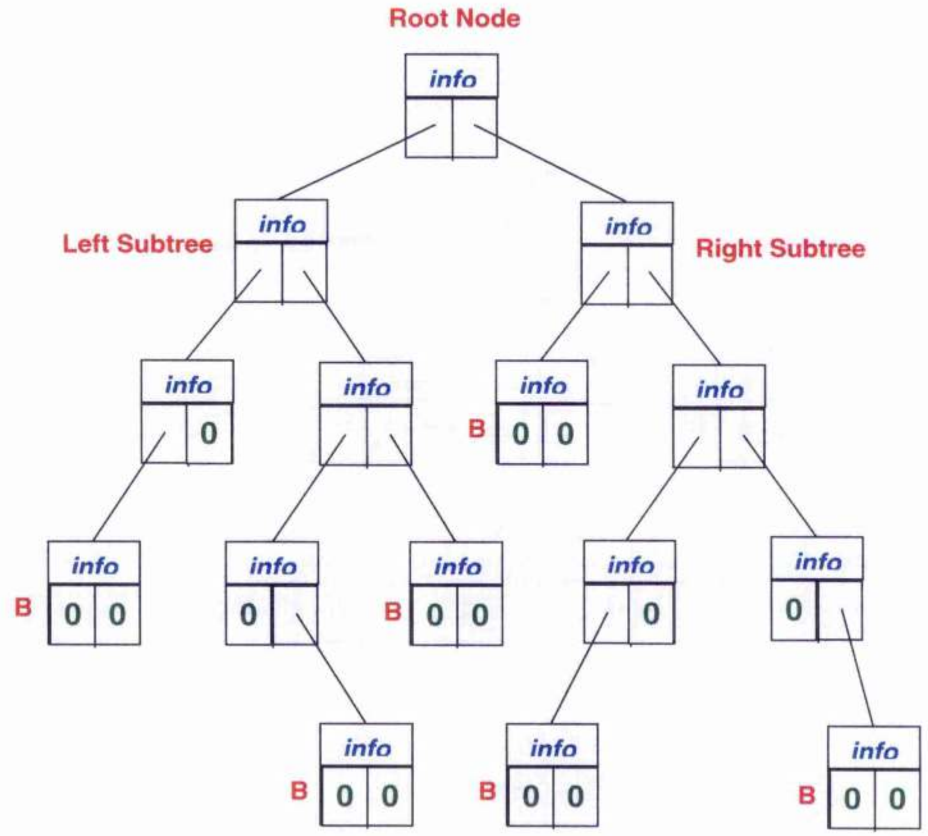
On average trees are more efficient than linked lists. This is because to reach a particular node in a linked list going through about half the list is needed. But with a tree each step visited eliminates a progressively larger number of nodes.

3.3.1 Bintree Representation

Schildt [1987] proposed the bintree (from: binary tree). A bintree is a tree in which each node can point to at most two other nodes. Each element in a bintree consists of information along with a link to the left (first) member and a link to the right (second) member, which are also elements of other trees. Each branch commences with a node and each node has multiple branches detaching from it.

FIGURE 3.5

A Bintree, where "0" Indicates a Null Pointer and "B" Indicates a Leaf Node



In the bintree structure, the root is the first element and it is generally shown at the top of the tree with its branches dropping from this root node. Branch nodes grow from the root and other branches. Branches attached to other branches are called sub-trees. In a bintree, each node except the root has a parent node. Each node is linked to another two sub-trees (maximum) or can have up to two children. A node without further sub-trees is called a leaf node or terminal node. Leaves are always at the bottom of their branches. Leaves can become branches when other leaves or branches are attached to them. Bintree structures are widely used in geometric modelling applications [Kawaguchi and Endo, 1980]. Figure 3.5 shows an example of a bintree structure.

3.3.3 CSG Tree Representation

As discussed, a 3-D object modelled through the combination of the basic volumes (blocks, cones etc.) or an extraction of one from another uses Constructive Solid Geometry (CSG). CSG is introduced in Chapter 2 and its further development as a tree is discussed in this section.

CSG is a binary tree with primitive objects in its leaves and set operations in the other nodes. Figure 3.6 (from Wikipedia) illustrates this.

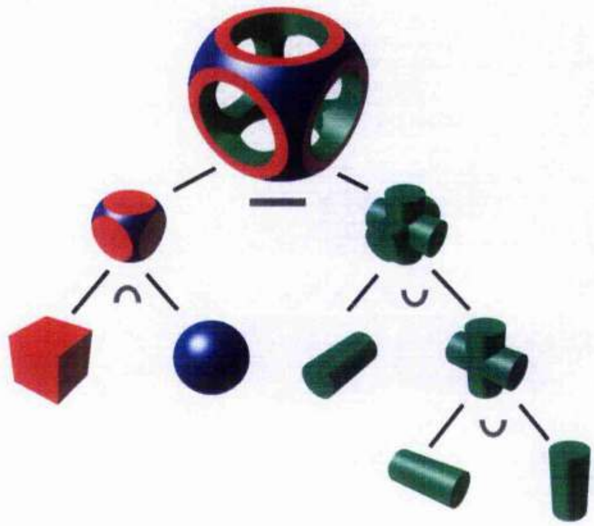
A scene represents various solid objects and empty space. CSG is one method of describing objects in the scene. Complex objects are built from simpler ones using set operations as detailed by Requicha and Voelcker [1983]. The geometry of a whole scene can be described, with primitive objects in the leaves and set operations in the nodes [Wyvill and Galin, 1997].

To model an object with CSG trees is an accepted method in 3-D modelling. But, this approach fails to obtain a *soft* (or gentle) transition between the different primitives composing the object [Wyvill, *et al.* 1986]. To have a realistic 3-D object model of an object, joining the primitives requires to be done smoothly. This problem is addressed by defining an implicit surface by its equation f $(x, y, z) = k$ [Wyvill, and van Overveld, 1997]. Based on specific implicit functions generating particular forms, many different implicit models exist; these control which elements blend together using a graph, but all are isolated implicit models [Bloomenthal and Shoemake, 1991].

FIGURE 3.6

CSG Tree Representation

(from: http://en.wikipedia.org/wiki/File:Csg_tree.png)



The first models combining implicit surfaces in CSG trees [Ricci, 1973] did not give soft transitions, whereas now most composition models support *blend* in the transitions. Pasko, *et al.* [1995] used the Boolean operators to compose functions, which was a very general approach; Wyvill and Galin [1997] limit their approach to skeleton based implicit surfaces, but treat blending and space warping in the same way as union, difference and intersection. Both approaches are very efficient.

Sabourdy, *et al.* [1996] developed a model using CSG binary trees to combine any implicit surfaces defined by an equation f $(x, y, z) = 0$. If f $(x, y, z) < 0$ then the point (x, y, z) is inside the object bound by the surface; if f $(x, y, z) > 0$ then the point (x, y, z) is outside). These are combined with exponential blending functions.

Kalameja [1995], Chiyokura [1988] and Dewey [1988] all explain that the CSG tree representation of an object can be ordered as a bintree when the leaves are either:

- primitives; or
- geometric transformations for mass and rigid body motions,

and, the non-terminal nodes are either:

- the standard Boolean operations (union, difference and intersect); or
- rigid-body motions (translation and/or rotation) that operate on their two sub-nodes (or sub-solids).

The root node represents the final object and each sub-tree presents the combinations and transformations [Onwubiko, 1989] building that final object.

3.4 Octree Representation

An octree (from: octant tree) is the most common 3-D spatial decomposition of the hierarchical representation of an object [Gargantini, 1992 and Meagher, 1982] that codes the recursive subdivision process of a finite cube referred to as 'the Universe'. The Universe is progressively subdivided into eight cubes of equal size [Mantyla, 1988]. In this approach, each node represents a cubical section (cube) of the Universe and contains a property value (e.g. **Full, Empty, Grey**) associated with that cube [Brunet, *et al.* 1989].

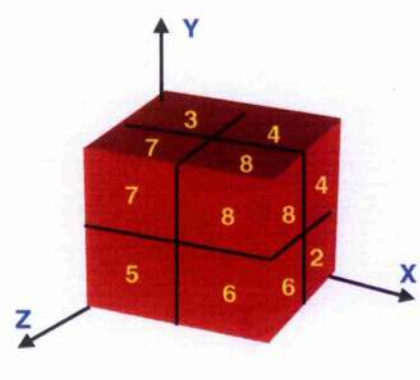
Chan, *et al.* [1989] explain the Universe as a cube of 2^n units edge length, where n represents the number of times the Universe is divided. For $n>0$, this cube is divided into eight cubes of equal size, with an edge length of 2^{n-1}, called octants. Any other node of the tree is associated with a cube having an edge length of 2^i where i points to the level of node in the tree. The octant with the smallest edge length 2^0 units (i.e. 1 unit) represents the resolution of the system [Tosiyasu, *et al.* 1985] and is referred to as the unit cube.

The root of the octree represents the entire space. Leaf nodes that are terminal nodes define octants containing unit cubes of the same value [Chen and Huang, 1988]. Leaf nodes do not contain primitives such as edges and polygons but approximate the object components by the cubes to the same degree of precision. If any one of the resulting nodes is homogenous then this means that the subdivision process has reached the end. If the node is heterogeneous, the node is further subdivided into eight sub-cells. The non-terminal nodes (grey nodes), which are heterogeneous or partially full must be divided into another eight cubic octants, until empty nodes (white nodes) or full nodes (black nodes) are obtained [Tosiyasu, *et al.* 1985].

To identify the location of an octant in 3-D space, a coordinate system such that one corner of the Universe stands at the origin and three of its edges lie on the positive x, y, and z-axes is used [Jackins and Tanimoto, 1980]. In order to specify this definition the size of the octant and the coordinates of a corner of it can define an octant's position. The specific information in a node has the limiting coordinates (x_{min}, x_{max}, y_{min}, y_{max}, z_{min}, z_{max}) of the octant. One unit of length along the axis is assumed to correspond to the length of an edge of a unit cube of the object array. An object array has standard orientation if the universe has its edges parallel to the positive direction of the axis. Figure 3.7 depicts the octant subdivision.

FIGURE 3.7

Octant Subdivision



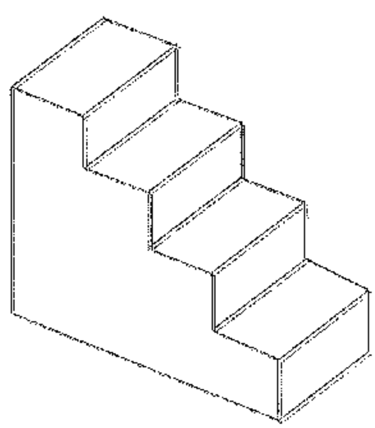
The Octree representation of an object is particularly convenient for Boolean operations [Brunet and Navazo, 1985]. The algorithms involved are linear and the computation of volumetric properties is very simple. These algorithms are based on integer arithmetic, which means that the analysis algorithms are fast and can be decomposed into parallel processes. Moreover, it is possible to use octree representation as a support or secondary model in CSG and B-rep [Cameron, 1991] representations. However, octree representation is also very useful for indexing space to specify the location of the major portion of an object and to refine, gradually, the description of the object's parts by providing more detailed indices [Gargantini, 1992].

When a real object is converted into an octree format, branch nodes at the lowest level are given a terminal value. This could be an empty node or a full node, respectively, if the object element is less or greater than half the occupied space. The number of nodes required to represent an object is a function of the size and shape of the object, its position and orientation when digitised and the level of resolution [Sadjadi, 1996].

Figure 3.8 shows a simple object that will be examined for octree representation in the following pages. Section 3.5 examines a real world implementation of the octree approach.

FIGURE 3.8

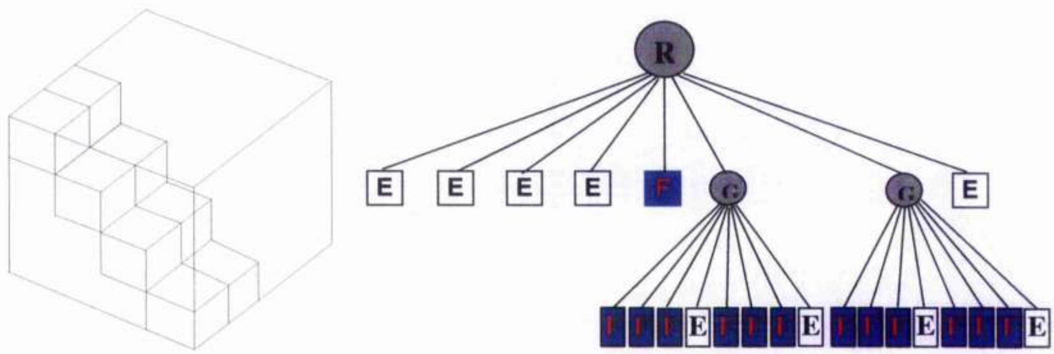
A Simple Architectural Object



For instance, regarding Figure 3.8, the object could be represented by the three levels of octree shown in Figure 3.9(b). Figure 3.9(a) shows the object inside its Universe.

FIGURE 3.9

(a) An Object Inside its Universe, (b) its Octree Representation: R, E, F and G stand for Root, Empty, Full and Grey Node Respectively



(a) (b)

3.4.1 Algorithm Considerations

Generally, the mathematical operations applied to octree structures that algorithms can draw on have several restrictions arising from speed, cost, implementation and simplicity considerations. The available operations are integer addition, subtraction and magnitude comparison. These operations involve simple arithmetic. Two phases of algorithm operation are defined, namely: set-up and run. During the set-up phase, a small number of computations are performed. For the run phase, a requested solid modelling function is performed over the octree objects [Samet and Webber, 1988].

For most of the algorithms, as Meagher [1982] has indicated, there are two categories of tree traversal: Depth-First and Breadth-First. Depth-First operations typically use a stack to maintain tree location and this traversal tends to be used when local information is required, whereas the Breadth-First algorithm processes all nodes at one level before working at the next lower level. Breadth first is employed from one level to the next in a queue when global information is needed. The Depth-First method is more commonly used and is discussed below in detail, using as an example the entity represented in Figures 3.8 and 3.9.

A Depth-First algorithm traverses a tree downward from parent to child, returning to the parent when all lower nodes have been processed. The major purpose of this type of encoding is to reduce the amount of storage [Jackins and Tanimoto, 1980] and redundancy. In this method, called Parenthesised Linear Notation [Brunet, 1992], every grey node's code is followed by the codes of its eight children and the sub-trees corresponding to every grey node are parenthesised.

Notation is based on the following symbols:

R	to represent the root node;
G	to represent a grey or non-homogeneous node;
E	to represent an empty node;
F	to encode a full node; and
( )	to show the level of branch node.

For example, as shown in Figure 3.9(b) for a tree representation, a total of 25 nodes are required and its linear encoding needs only 50 bits, since the type of every root, empty, full or grey node can be stored in two bits. The Depth-First expression of tree representation of Figure 3.9(b) can be shown as follows:

R(EEEEFG(FFFEFFFE)G(FFFEFFFE)E)

Where E, F and G denote Empty, Full and Grey nodes respectively and R is a Root node.

Gargantini [1982] coded an implicit tree with octree encoding using the full nodes of the tree. In this algorithm, the full nodes are stored, successively, with their spatial position and the size of the nodes. In a Universe with an edge length of 2^n and a resolution of 2^0, each full node is coded with n digits. For example, the encoding of the tree at level 2 in Figure 3.9(b) is numbered: 61, 62, 63, 65, 66, 67, 71, 72, 73, 75, 76 and 77. As shown in the above figure, the final tree has 6 full nodes at level 2. (It can be noted that a voxel surface is represented by a series of pattern codes. The pattern codes carry out the information of the local shape of the voxel surface.)

Samet and Webber [1988] proposed an effective encoding of octrees as an explicit tree. This algorithm carries the information about the node type (Empty, Full or Grey), eight pointers from a grey node to its children and a pointer to the level of node in the tree.

With reference to the explanation in Section 3.3 concerning accessing a tree structure, it has been concluded that, for octree encoding, the optimal method of encoding depends on the application. For instance, with a linear operation such as a traversing, Brunet and Navazo (1992) explain that the number of accesses is proportional to N (the number of nodes), whereas with a non-linear operation such as point classification (is the point inside or outside a solid?) the number of accesses is proportional to log N.

3.4.2 Advantages and Disadvantages of the Octree Technique

In an octree representation, any arbitrarily shaped objects, convex or concave or with interior holes, can be modelled to the precision of the smallest voxel. According to Kouvaris [1992] octree representation is an appropriate method for solid modelling. There are many algorithms to generate an octree model from another solid representation such as CSG. For the computation of Boolean operations, geometric properties and rendering*, octree representation is an effective structure [Saito, *et al.* 1993]. Properties of an object such as its centre of gravity, mass, surface area and moments of inertia are calculated easily by an octree method at different levels of precision [Frieder, *et al.* 1985]. Therefore, octree representation can perform better than B-rep on Boolean Operations and it is preferable to CSG for volume properties [Brunet, 1992]. These conclusions are summarised in Table 3.1, based on work by Brunet, *et al.* [1985]. This table compares the performance of octree representation with B-rep and CSG on the Boolean Operations, volume properties' determinations, geometric transformations and rendering. The Octree technique comes out well.
Nevertheless, the octree data structure suffers from several limitations. The major limitation of the octree data structure is the difficulty of incorporating it into existing graphics software systems. For instance, most computer systems are built typically around either a boundary representation (B-rep) scheme or primitive solids with these

being combined into complex objects by CSG methods. An object created on such a system and transformed into an octree to take advantage of set operations, can no longer be reconstructed exactly [Ayala, *et al.* 1985].

TABLE 3.1

Performances of Different Solid Representations

	Boolean Operations	Volume Properties	Geometric Transformation	Rendering
Octree	Good	Good	Bad	Good
B-rep	Bad	Good	Good	Good
CSG	Good	Bad	Good	Average

In octree representation, the bounding surface of an object is represented by the set of square facets between the empty and full cells. Thus, these approximate the original surface by square polygons that are parallel to the sides of the original universe space [McMahon and Browne, 1993]. For an object with complex detail, octree representation requires a large number of cells to represent the object accurately. Given that the number of subdivisions is limited, an octree is an approximation of an object and properties (e.g. curvature) of the object can be calculated [Kela, 1989]. Precise detail such as surface curvature is often lost in the octree representation. Otherwise, for objects with curved boundaries, the degree of precision of the model depends on the cell size [Davies and Yarwood, 1986], this can be referred to as a resolution constraint. Curvature is a particular concern of architects.

An octree structure provides a hierarchical representation applicable to a wide class of objects and it supports the computation of several geometrical properties. However, as well as imposing resolution constraints, octree representation suffers from not being able to link intelligence to it as easily as B-rep. This is a drawback for this form of representation to set against its many advantages.

In the following section (Section 3.5) a real example re-examines octree representation. This example shows how a digital surface model has been converted to an octree representation.

** **Rendering** is the process of generating an image from a model, by means of computer programs. The model is a description of three-dimensional objects in a strictly defined language or data structure. It would contain geometry, viewpoint, texture, lighting, and shading information. The image is a digital image or raster graphics image. The term may be by analogy with an "artist's rendering" of a scene. 'Rendering' is also used to describe the process of calculating effects in a video editing file to produce final video output (from: Wikipedia).*

3.5 Real World Example of Octree Representation

The real world example given here considers the Newcastle University Debating Chamber (NUDC). NUDC is a 1960's building located at the University of Newcastle upon Tyne, which was surveyed by the author in 1995 and has been modelled using a digital surface modelling technique. The *3Dpoly* function of AutoCAD is a convenient AutoCAD function for representing a building and has been used to model this example, in 3-D.

AutoCAD reads all surveyed coordinates from a text file. *3Dpoly* ensures the connectivity of these vertices automatically, with the last and first points of a polygon coinciding. A script file, *3Dpoly.scr*, contains a list of all the planes of a building. All the vertices are stored as 3-D coordinate points, with each set of these vertices representing a plane (or face) of the building. Table 3.2 shows the vertices, which create the 3-D polygons of the NUDC.

TABLE 3.2

Vertices for the Creation of a Wire-frame Model of the NUDC

Name of 3DPoly	*Vertex No.*	*End Point (Last Vertex)*
Top Plane (TP)	3, 6, 5, 4	Closed on Vertex No. 3
Bottom Plane (BP)	2, 30, 31, 38, 39, 7 8, 24, 21, 16, 13, 1	Closed on Vertex No. 2
Base of Column (C_1)	28, 25, 26, 27	Closed on Vertex No. 28
Base of Column (C_2)	36, 33, 34, 35	Closed on Vertex No. 36
Base of Column (C_3)	20, 17, 18, 19	Closed on Vertex No. 20
Base of Column (C_4)	12, 9, 10, 11	Closed on Vertex No. 12

The above six polygons (wire-frame models) have been drawn using the minimum data. These six polygons are the bottom plane (BP), top plane (TP) and four columns of the building (C_1, C_2, C_3 and C_4). The extra four points (16, 21, 31, 38) considered in the BP are used, by *3Dpoly*, to complete the columns. A wire-frame model of these planes (polygons) is shown in Figure 3.10.

FIGURE 3.10

Shows Six Polygons (Wire-frame Model) Drawn by *3Dpoly* Method

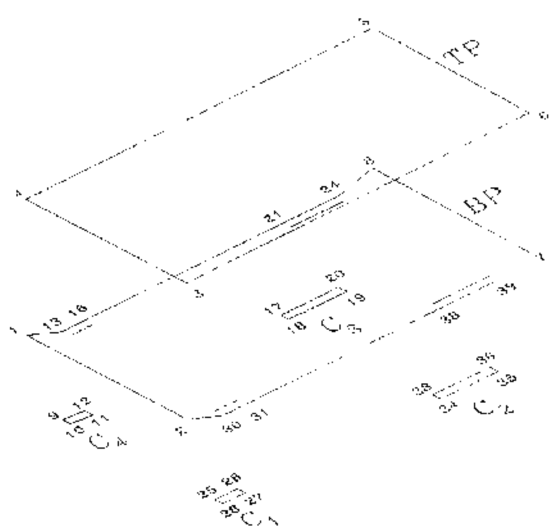


Figure 3.10 has enough information (the minimum data) on points and edges to carry out the modelling of the building using a wire-frame model. To minimise the task,

(data storage and computing time), all the forty points have been drawn. Later, using the *3DFace* command the side planes or the faces of each column can be made. Using the minimum data with this command, the whole shape of the building can be modelled. The four horizontal planes (13, 14, 15, 16), (21, 22, 23, 24), (29, 30, 31, 32) and (37, 38, 39, 40) have not been drawn but instead only unlabelled lines have been produced for each of them i.e. (14, 15), (22, 23), (29, 32) and (37, 40), and these lines are used to complete the columns of the building - even if they are later removed from a visualisation as 'hidden lines'.

The *3DPoly* command is used to construct the building. In AutoCAD, 3-D faces are modelled as 3-D polygonal surface meshes. 3-D faces can be constructed as flat surfaces (planar) or as non-planar surfaces. Each Three-Dimensional face is either a triangle or a quadrilateral. Figure 3.11 shows that the BP is a non-planar surface. The dashed lines 13-30 and 24-39 are the bends of this surface. These two lines have bent the BP. These two lines will be used to divide this 3-D polygonal surface mesh.

FIGURE 3.11

Shows the Bends on the Bottom Plane of the NUDC

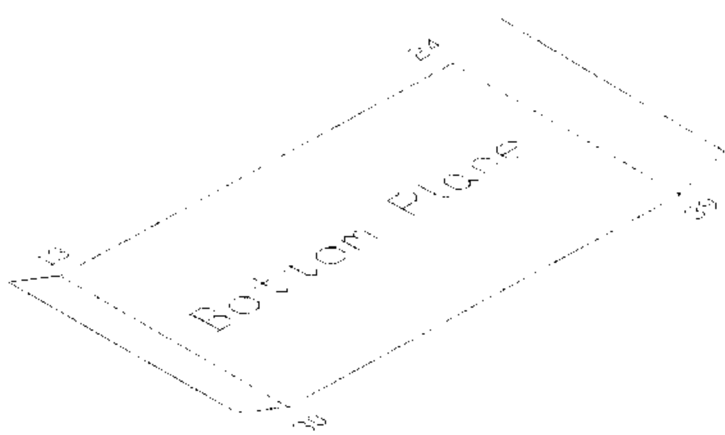
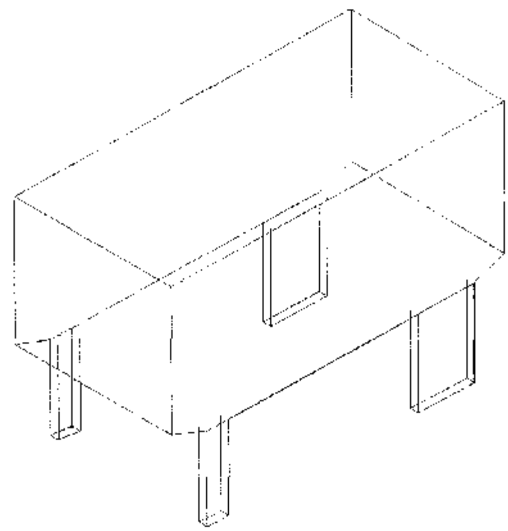


FIGURE 3.12

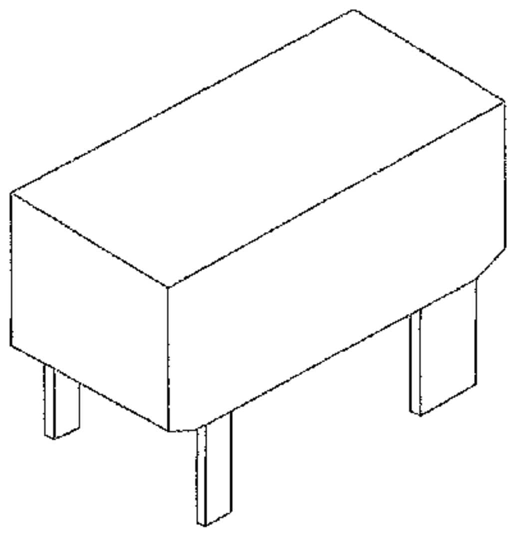
Shows a 3-D Wire-frame Model of the NUDC



A wire-frame model of the NUDC has been created in Figure 3.12. Finally, the hidden-line removal command is used to remove the lines behind the surfaces in order to obtain the 3-D digital surface model of the NUDC as shown in Figure 3.13.

FIGURE 3.13

Shows a 3-D Digital Surface Model of the NUDC



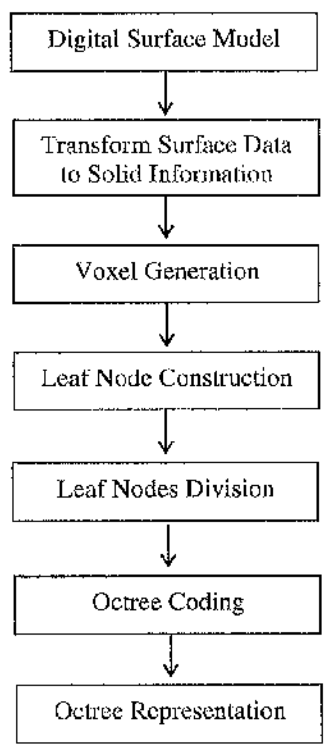
Octree representation describes the NUDC by a spatial geometric structure. The conversion from this digital surface model to the octree representation is the goal of the rest of this section. A detailed description of the algorithm for the reconstruction of a digital surface model to an octree representation can be found in Figure 3.13.

A hot link between digital image matching and AutoCAD converts a digital surface model of the NUDC into an octree representation. The digital surface model is transformed from a network data structure into voxels.

According to the field measurements made of the NUDC's components, an octree representation of the NUDC (Figure 3.15b) can be created showing the representation determined to five levels, i.e. Level I contains only the root whereas Level II consists of two Grey nodes (1,3), two Full nodes (5,7) and four Empty nodes (2,4,6,8) etc. Further subdivisions results in no grey nodes at level five, but 128 leaf nodes which are either Full or Empty.

FIGURE 3.14

A Scheme for the Conversion of a Surface Modelling to an Octree Model



A hot link between digital image matching and AutoCAD converts a digital surface model of the NUDC into an octree representation. The digital surface model is transformed from a network data structure into voxels.

The main point of conversion from a digital surface model to an octree representation is to transform surface data to a volume based representation.

FIGURE 3.15(a)

Octree Representation of NUDC

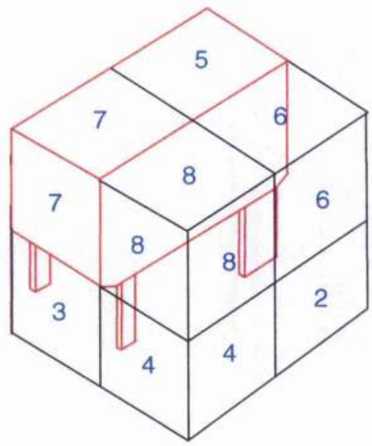


FIGURE 3.15b The Linear Octree of NUDC (derived from Fig 3.15a)

```
R(G(G(G(FEFEFEFE)EEEG(FEFEFEFE)EEE)G(EG(EFEFEFEF)EEEG(EFEFEFEF)EE)EE
G(G(FEFEFEFE)EEEG(FEFEFEFE)EEE)G(EG(EFEFEFEF)EEEG(EFEFEFEF)EE)EE)EG
(EEG(EEG(FEFEFEFE)EEEG(FEFEFEFE)E)G(EEEG(EFEFEFEF)EEEG(EFEFEFEF))EE
G(EEG(FEFEFEFE)EEEG(FEFEFEFE)E)G(EEG(EFEFEFEF)EEEG(EFEFEFEF)E))EFEFE)
```

Details of the divisions and subdivisions, with only grey levels expanded follow:

Level I:	R
Level II:	G EG EFEFE
Level III:	G G EE G G EE EEG G EE G G
Level IV:	G EEEG EEE EG EEEG EE
	G EEEG EEE EG EEEG EE
	EEG EEEG E EEEG EEEG
	EEG EEEG E EEG EEEG E
Level V:	FEFEFEFE FEFEFEFE EFEFEFEF EFEFEFEF
	FEFEFEFE FEFEFEFE EFEFEFEF EFEFEFEF
	FEFEFEFE FEFEFEFE EFEFEFEF EFEFEFEF
	FEFEFEFE FEFEFEFE EFEFEFEF EFEFEFEF

3.6 Summary and Conclusions

This chapter has reviewed some well-known data structures. Possible data structures for graphic systems have been implemented.

Linked list data structures are built with pointers that link the separate objects into a single data structure. The linked list data structures have been described at two levels; singly linked lists and doubly linked lists. Tree data structures that are used to represent data having a hierarchical relationship are considered. The octant data structure (octree) has been presented; an octree representation, which approximates geometric models by equally sized solid cubes, is a prevalent hierarchical representation of 3-D objects. One of the simplest octrees that only allows homogeneous terminal nodes is called the *classical octree*. An example octree structure as a representation of 3-D objects is presented.

Octree techniques can be extended and applied to solid modelling for the purposes of 3-D representation in the reconstruction and restoration of historical buildings.

An application of the octree approach, proposed by the author, could be used to visualise internal damage to a building, even if nothing shows externally. A strategically important structure (such as a dam) or a culturally important structure (such as an ancient temple) may be continually measured (perhaps using permanently installed EDM equipment). Such measurements can be used to produce an octree representation. If the octree representation is generated at regular intervals, changes in the structure can be highlighted and localised by visualising changes in the octree representation. Changes in the F or E or G status of a voxel may indicate structural deterioration, even without any obvious external deterioration.

Object modelling requires data capture, data sampling and data structuring that is recursively updated, depending on the method of 3-D representation. Octree representation supports recursive update, but a linked list structure does not.

As the result of the investigation in this chapter, an octree representation was produced (Figures 3.14 a, b), using coordinates obtained by survey methods. Another solid object, a part of a monument (the Hunter Memorial) will be examined in Chapter 8. Some comparisons between octree representations, B-rep and CSG were made, based on the Boolean Operations, volume properties, geometric transformations and rendering, with the results presented in Table 3.1.

The implementation of analyses has proved difficult with many of the available data structures, and this may be examined in the future. However, this chapter has included examples describing how the octree approach can be used to handle 3-D modelling. Figure 3.7 shows an example solid object whose subdivision has been terminated at level 3 and Figure 3.12 whose subdivision has been terminated at level 5, at which point all the nodes are either Full (F) or Empty (E).

4. Tools for Modelling Cultural Objects

4.1 Introduction

The aim of this chapter is to review: photogrammetry; Geographic Information Systems (GIS); visualisation; rendering; and, Computer Aided Design (CAD), in the context of modelling cultural objects. These are all sets of tools which can be used to assist in modelling cultural objects, assuming a collection of appropriate input data for such cultural objects.

4.2 Photogrammetry Applied to Modelling Cultural Objects

Starting with Laussedat's close range photogrammetric work in the 1850's, the use of stereo-photogrammetry for recording cultural heritage has advanced steadily; Meydenbauer established an archival institution in Berlin, in 1885, where photographs appropriate for the reconstruction of damaged buildings could be stored [Atkinson, 2001]. These ideas were adopted in several other countries and by 1926 the (then) International Society for Photogrammetry had established a technical commission for architectural photogrammetry [Atkinson, 2001].

A photogrammetric project involving the modelling of a cultural object attracted widespread interest in late 1992. The project arose as a consequence of the destruction, by fire, of the State Apartments at Windsor Castle and involved the production of engineering drawings for the renovation of the apartments using terrestrial photogrammetric techniques. This project is reviewed in this section, with the aim of presenting the position before the potential of digital photogrammetry in cultural modelling was recognised. From this description good practice transferrable to a digital approach can be identified.

A major fire broke out in the State Apartments at Windsor Castle in November 1992; within 48 hours of the fire erupting, English Heritage's Survey Service had inspected the site and a Steering Committee had been formed to guide the restoration of the damaged parts of the building [Dallas *et al.*, 1995]. It was quickly established that a 'photogrammetric programme' was to provide the base for planning repairs. According to Dallas *et al.* [1995], there were two phases to this programme:

1. using some 100 'pre-fire' 1:80 scale photographs taken with a Zeiss UMK 10/1318 camera, of part of the damaged area to produce 1:20 scale plots and 1:20 scale rectified photos; and,
2. using 8 sets of 'post-fire' 1:80 scale photographs to produce 8 sets of 1:20 scale plots and 1:20 scale rectified photos.

The original 'pre-fire' photography was taken by the Department of Environment's Property Services Agency, in 1985. Two different companies produced the plots and rectified photographs. In the second phase, some four companies were involved in plotting, each responsible for its own photography. On completion of the plots, these were digitised as so-called 'separated object areas' and a geospatial database created in AutoCAD v12. The 'separated object areas' can be considered equivalent to 'facets', and can be seen in Figure 4.1. Polylines and polygons were captured and recorded using 3-D coordinates, to form the separated object areas. Further output related to the 'post-fire' photography included colour photos.

According to Dallas *et al.* [1995] and Dallas [1996], the plots recorded:

- architectural detail; and,
- stonework jointing,

using a three-dimensional coordinate system. In addition details on:

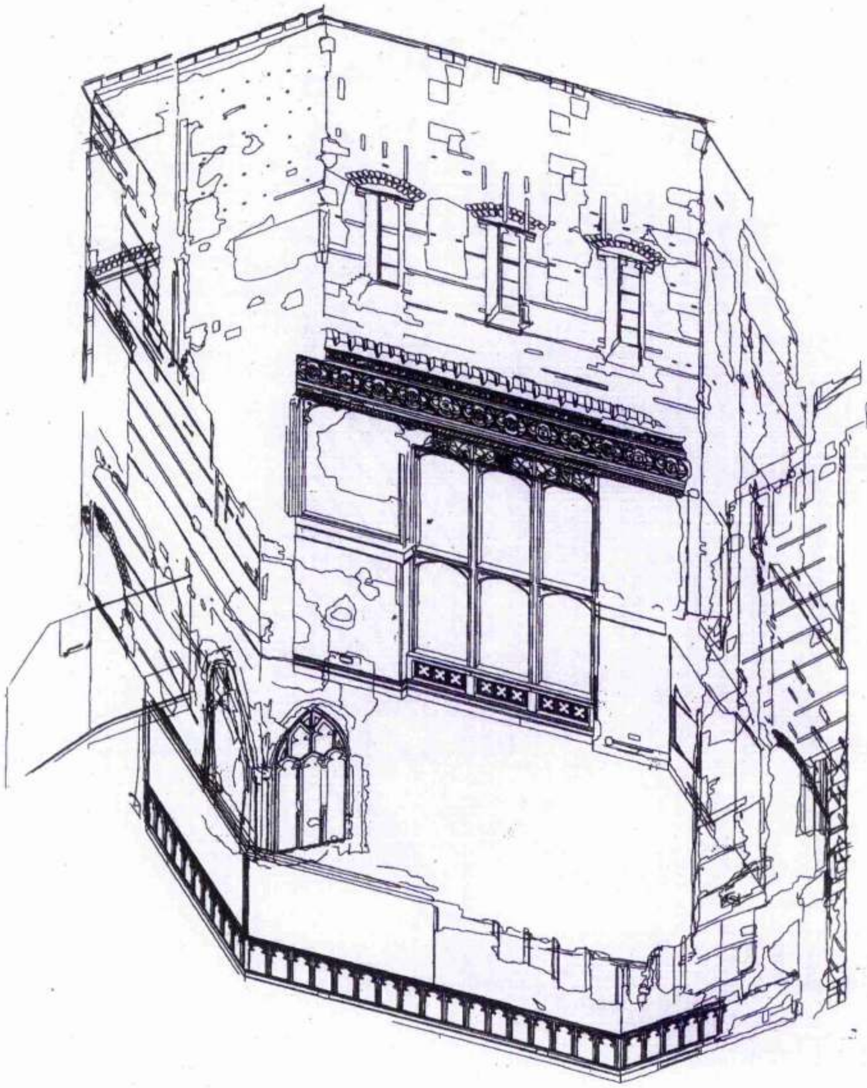
- material and the different types of stone, brick and wood used;
- mouldings (which can be used for dating);
- mortar types, locations (areas) of different types identified;
- pointing, locations (areas) of different types identified and plotted;
- pecking and other surface finishes;

- graffiti and other masons' marks; and,
- blocking, patches, changes of building practices, erosion, weather and fire damage

were recorded "using a combination of text and pictorial representations" [Dallas *et al.*, 1995].

FIGURE 4.1

A 3-D View of Separated Object Areas in Windsor Castle Based on Multiple Facets (from [Dallas *et al.*, 1995])



In this Windsor Castle project, the rectified photos were found very useful by the archaeologists, who could add details of features to them, which had not been picked up by the photogrammetrist. In the Dallas *et al.* [1995] and Dallas [1996] publications, there is no record of digitising this additional detail off the rectified photos although, it does seem an obvious step to take, especially as Dallas reports that some areas which could not be accessed by the camera were hand sketched and these sketches were then digitised and fitted into the data sets derived from the 'post-fire' 1:20 scale plots. These sketches were done on A3 boards onto which the AutoCAD details for the surrounding, photogrammetrically accessible areas had been plotted.

The Dallas *et al.* [1995] and Dallas [1996] publications clearly present the historic background to the project, the photogrammetric tasks to be carried out and the outcome of each task in general terms, but the specific details are not present. However, reference is made to a 1988 publication "A specification for the Architectural Photogrammetric Survey of Historic Buildings" as containing what had become prescribed procedures for photo-control and targeting, photo-scales, photo coverage, plotting scales, drawing content, and the accuracies of many components. These procedures have since then undergone revision and have been published by English Heritage [Bryan and Blake, 2000]. This newer publication contains a wealth of detail pertaining to the production of photogrammetric plots of architectural objects, but the environment is still considered that of hardcopy photogrammetry and CAD. Nevertheless, to guide the outcome of the work reported in this thesis, the English Heritage document contains much valuable information.

A summary of this approximately 70 page document "A specification for the Architectural Photogrammetric Survey of Historic Buildings" follows:

1. Photo Control Points

- Coordinates of targets to be determined with an accuracy of +/- 4mm or better;
- At least 4 targeted control points per stereo-pair;

- Targets to be of 'butterfly' design with a matt finish, dimensions no greater than 40mm x 60mm x 0.5mm, and uniquely numbered so that the numbering will be discernible in photography viewed at x8 illumination;
- Targets to be attached with a non-marking non-destructive adhesive (guidance may have to be sought regarding the adhesive when the target is to be attached to certain historic fabrics);

2. Imagery

- Image platforms must be specifically manufactured or adapted for close-range photogrammetry;
- Image format to be 60mm x 60mm or greater;
- A fixed focal length camera is to be available, with the focal length known to within 0.01mm;
- A copy of the camera calibration report to be available;
- A film transport system that ensures film flatness for each exposure;
- Minimum Photo scales of 1:200, 1:100 and 1:50 required for 1:50, 1:20 and 1:10 plots respectively;
- In the event of digital imagery being used, the pixel size is not to exceed 25 micrometers;
- Base: Object ratio is 1:4, or less. (It can be noted that there is probably an error in English Heritage's published Base: Object ratio requirement.);
- Stereo overlap 60% or more;

3. Fiducial Marks

- At least four (self-illuminating) fiducial marks per image to be visible;
- Accuracies achieved during each interior orientation to be recorded;

4. Product Accuracy

- For well defined detail RMSE of 0.3mm at map scale. Thus, for a 1:50 scale plot, the RMSE is about 15mm (and for 1:20 scale plots the RMSE is 6mm);

5. Digital Data

- All file names are to be eight characters long, including a standardised 3-character abbreviation for the monument; 2-character abbreviation for the year of photography; 1 character code for the type of survey; 2 character sequential number;
- CAD file format to be AutoCAD.DWG;
- Raster format to be TIFF or BMP;
- Provided on a CD ROM;
- All data to be provided in two 3D coordinate systems; WCS (i.e. National Grid for Great Britain) and a user coordinate system (UCS) having its x-y plane 'square-on' to each building face with an origin in the bottom left corner of the building face having a value of 10m for X, 10m for Z, and the true value for Y;
- DEM (for orthophoto generation) spacing 10cm or less and break lines;

6. Plots

- Recommended scales are 1:10, 1:20 or 1:50;
- The drawing unit to be 1.00m;
- Blocks to be drawn as closed polygons;
- Mortar joints to be a polyline snapped to adjoining blocks;
- Captured detail to include windows, doors, fireplaces, jambs, sills, lintels, masonry immediately surrounding a feature, etc.;
- For polyline and polygon features, the maximum spacing between recorded points is 3cm at ground scale;
- Points must be recorded in polyline and polygon features where there are corners and distinct changes in direction;

7. CAD Layers

- Facing stone (white);
- Core work exposed by the removal of facing stone (red);
- Windows/doors/ fireplaces (yellow);

- Architectural fragments (green);
- Sculptural details (Cyan);
- Modern services (Magenta);
- Annotation (Blue); and,
- Control Points (White).

The conclusion which can be drawn from this review of the Windsor Castle project is that, following the established guidelines of the main contractor (English Heritage), as outlined above, a series of terrestrial photogrammetric surveys was successfully completed. It would be beneficial to assume that, whenever possible, the procedures developed in the investigations reported in this thesis considered these English Heritage guidelines.

The English Heritage guidelines were for non-digital photogrammetry. In the work subsequently carried out by the author, a variety of digital cameras (Kodak DC260 and DC4800; Sony DSC-F828; Fujifilm A920) and a terrestrial frame survey camera (UMK 10/1318 Zeiss), with subsequently scan digitised photos, were used to capture the data. A separate 1" theodolite was used to obtain the ground control point coordinates, with tape measurement when distance measurements were required and the use of a local coordinate system.

Terrestrial photogrammetry based on digital imagery has a potentially important place. It can be used for the documentation of monuments, recording their decay and supporting their development, maintenance and reconstruction [Marten *et al.*, 1994]. 3-D data representation or models are needed for a variety of restorative applications. Digital photogrammetry offers the potential of supplying data for these. Digital photogrammetry also has the potential to supply textural information from orthophotographs of faces/façades that can be used in the rendering of 3-D models produced from photogrammetrically derived X, Y, Z points.

4.2.1 Developments in Photogrammetry

In 1924, Otto von Gruber derived the **collinearity equations**, which are fundamental to photogrammetry. Presented for completeness, these show the relationship between object coordinates in ground units (X,Y,Z) and the photo coordinates (x,y) of a point:

$$\mathbf{X\text{-}Xo} \quad = \quad \mathbf{(Z\text{-}Zo)} \quad . \quad \frac{\mathbf{m_{11}(x\text{-}x_o)+m_{21}(y\text{-}y_o)+m_{31}(\text{-}f)}}{\mathbf{m_{13}(x\text{-}x_o)+m_{23}(y\text{-}y_o)+m_{33}(\text{-}f)}}$$

$$\mathbf{Y\text{-}Yo} \quad = \quad \mathbf{(Z\text{-}Zo)} \quad . \quad \frac{\mathbf{m_{12}(x\text{-}x_o)+m_{22}(y\text{-}y_o)+m_{32}(\text{-}f)}}{\mathbf{m_{13}(x\text{-}x_o)+m_{23}(y\text{-}y_o)+m_{33}(\text{-}f)}}$$

where:

f is the camera lens' focal length

xo, yo are the photo coordinates of the principal point

Xo, Yo, Zo are the camera station coordinates in ground units

$\mathbf{m_{11}}$ = Cos (ϕ).Cos(κ)

$\mathbf{m_{12}}$ = Sin(ω).Sin(ϕ).Cos(κ) + Cos(ω).Sin(κ)

$\mathbf{m_{13}}$ = -Cos(ω).Sin(ϕ).Cos(κ) + Sin(ω).Sin(κ)

$\mathbf{m_{21}}$ = -Cos(ϕ).Sin(κ)

$\mathbf{m_{22}}$ = -Sin(ω).Sin(ϕ).Sin(κ) + Cos(ω).Cos(κ)

$\mathbf{m_{23}}$ = Cos(ω).Sin(ϕ).Sin(κ) + Sin(ω).Cos(κ)

$\mathbf{m_{31}}$ = Sin(ϕ)

$\mathbf{m_{32}}$ = -Sin(ω).Cos(ϕ)

$\mathbf{m_{33}}$ = Cos(ω).Cos(ϕ)

and where:

ω = angle of rotation (tilt angle) of the camera around its x-axis

ϕ = angle of rotation (tilt angle) of the camera around its y-axis

κ = angle of rotation (tilt angle) of the camera around its z-axis

These equations can also be presented to show the relationship between raw photo-coordinates and those that have been corrected for tilt. In either form they are extremely useful and embedded in the photogrammetric software used in this research.

Photogrammetric measurement instrumentation used to extract photocoordinates (**x,y** above) from photographs to model cultural objects can be divided into four classes based on the degree of computerisation [Torlegard, 1986]. These are:

1. analogue instrumentation;
2. numerical instrumentation;
3. analytical instrumentation; and,
4. digital instrumentation.

The first three use hardcopy photographs. The fourth, digital instrumentation, sometimes called softcopy photogrammetric instrumentation or a Digital Photogrammetric Workstation, uses data files representing the scanned photographs or digital images, rather than hardcopy photographs. In this class, images are digitally stored in the computer, where they can be processed and displayed on the graphics screen [Bähr and Wiesel, 1991]. This environment allows photogrammetric tasks to be integrated with tools already well established in the digital image processing and geospatial communities. The digital image can be collected by scanning photographs or by collecting the image directly using a digital camera. In digital photogrammetry, photos used as digital image data have varying resolutions from 1μm pixels to 100μm (or larger) pixels.

Both hardcopy and softcopy photogrammetry support 3-D data capture, but digital photogrammetry and softcopy imagery have advantages over hardcopy approaches, such as the ability, easily:

- to support digital image processing;
- to display vector data in the images on the screen;
- to create transformed images (rectification, orthorectification);
- to create output presented as 3-D models;
- to export 3-D data into CAD (and other) systems; and,

- to produce orthophoto mosaics, hierarchical/layered polygons, high-density point clouds or data in Web-formats.

These tasks are carried out in an environment of softcopy workstations which are now relatively less expensive than analytical/analogue plotting devices were (where special hardware was needed). Transferring data between software systems can be simplified because they can be post-processed on the same computer.

For these reasons, digital photogrammetry is advocated as the primary data capture method for cultural monument conservation.

Working with three-dimensional computer models is becoming standard in architectural and archaeological projects, and in the projects investigated in the next chapter integration of digital photogrammetry, CAD (Computer Aided Design) and GIS (Geographical Information Systems) packages is evident.

Traditionally, when recording for archival purposes, a rough drawing was made of a cultural monument, dimensions of the monument were measured manually and appended to the drawing, and then the conditions, materials, colours etc. were noted. Next the recorders would move to the drafting board and convert these notes into dimensioned drawings. Manual recording is still being carried out, but frequently, now, restoration architects thereafter transfer the rough drawings to a CAD system for use. Nevertheless even these updated procedures may be more time consuming than necessary, and opportunities have been provided by photogrammetry to make them more efficient.

Recently, those involved with recording cultural monuments have turned their attention to the possibility of collecting the relevant information without the traditional architectural drawing. It is now thought that workers should be able to analyse, display, present, restore, maintain, monitor and reconstruct the monument, based on coordinates and other digitally gathered and recorded information [Mencl, 1995] rather than the traditional drawing. Generation of a true 3-D model such as a wire-frame or digital surface model is a stage in the process [Vosselman and

Veldhuis, 1999]. The vector-based model so created can be imported into an object-based information system where, as an object, it is linked to a database. Architectural elements can be represented as individual objects within the environment of the information system.

Software tools are available not only to assist in the assembly and establishment of the objects but also to enable the query and display of the information required for heritage purposes. But what is required for these purposes? If found, the answer to this question will offer a data acquisition strategy for creating a database of all available information that can be easily explored. The database is not only for generating the drawings but also should be the record of the history of the cultural object(s). As well as a record of the building or site in the form of spatial coordinates, the database should consist of collected data and references from the site, photographs, documents, records, measurements, scanned images of original drawings, etc. The documents and records need not be limited to information that can be easily expressed in the form of drawings and written reports; also there can be photos, orthophotos, videos, linked projects etc. A cultural site's information system should be a stable and comprehensive database of all known information.

It is the integration of close-range digital images, photogrammetry (with the required land survey), CAD and GIS tools, which is considered the basis for recording the main physical details of the cultural objects of interest. But despite the many advantages of digital images there are problems connected with image acquisition. For many applications, the format of the CCD cameras that are commercially available is too small, the resolution is too low. Therefore, one may be obliged to use hardcopy photographs. Those photographs have to be scanned, using photogrammetric scanners. Usually the photographs to be scanned have been captured using metric cameras.

Uki Helava, along with Salem Masry of the University of New Brunswick and Universal Systems, Fredericton, played central roles in the development of digital photogrammetry. At Helava Associates, Inc. formed in 1979 to eventually become, in 1986, a subsidiary of General Dynamics, Helava helped develop digital photogrammetric workstations for the United States Defence Mapping Agency. The company BAE Systems is now "guardian" of Helava and Masry's original concepts and has provided support for SOCET SET one of the digital photogrammetric packages used at Glasgow University.

Throughout almost all its 40-year history, digital photogrammetry has been commercialised by companies usually associated with defence. Consequently, production costs have been left high. However, interest from environmentalists, in particular, has now obliged the manufacturers to supply digital photogrammetric software running on low-end platforms. At the University of Glasgow, the recent transfer of its SOCET SET licence from a UNIX platform to Windows platforms demonstrates this. Now on more popular platforms it is envisaged that architects and archaeologists - - as well as Geomaticians - will utilize the software much more.

The bulk of publicly funded topographic mapping carried out worldwide for the last fifty years has utilized aerial photogrammetry. But, having emerged in the nineteenth century and subsequently undergoing an eclipse by aerial photogrammetry, now once again terrestrial photogrammetry is an important technique in photogrammetric science. In terrestrial photogrammetry, photographs are obtained from ground-based cameras; most photography for cultural applications uses ground based cameras.

Once, prevalent among these cameras were phototheodolites. Phototheodolites represented a connection of camera, theodolite and tripod. Combined with the theodolite, the measurements of tilt angles (see the collinearity equations above, in this section), distances and elevations are possible [Wolf, 1983], all in the same operation as taking the photographs. Now, in terrestrial photogrammetry, a variety of cameras are used including the standard film-based 35-mm cameras, low end and professional digital cameras. When a film-based camera is used, how a film is scanned for use in computer processing must be considered. Scanners involve mechanically scanning a sensor or mechanically shifting the film. It means that the scanners add a further distortion to the image acquired on film. Making mechanical movements precise can be expensive and many low-end consumer-grade scanners are not very precise.

Arising from a diversity of photo measurement procedures the resulting 3-D coordinates can be input to a CAD, or equivalent, system for further processing or visualisation. The benefits of this technique over purely field procedures are: decreased costs and reduced on-site time, potentially increased accuracy arising from a more comfortable working environment and the chance of 're survey' should some items be missed at the 'first mapping'.

The main steps in close-range photogrammetry are to:

- ensure that a well-calibrated (or equivalent) camera is used for the project;
- plan the camera station locations ensuring stereo coverage;
- establish a network of control points;
- set up a reference system to support transformation between the photographs and the real world; and,
- take the photographs of the object.

Other tasks in terrestrial photogrammetry involve safeguards which minimise the errors and maximise the measurement accuracy:

- maximise the number of photographs that each point is 'marked' on;
- ensure that all points appear on two or more photographs;
- minimise the number of points that appear on only two photographs;
- introduce convergence between the camera positions when possible;
- make sure the photographs have good coverage; and,
- ensure that all point and line 'markings' inserted into the images are precise.

Control points are needed to calculate the location and orientation of photographs. These control points are ideally identified prior to photography and normally consist of stick-on targeted points that are clearly labelled, in a way which can be read in the photograph. Although theoretically three are adequate, in practice a minimum of six control points (targetted or untargetted) need to appear in that part of every photograph used for measurement. The X,Y,Z coordinates of each point can be identified in a Local (LCS) or World Coordinate System (WCS). This can be achieved by either surveying the control points using a theodolite or total-station, or by measuring the distances between the various control points and establishing an arbitrary coordinate system [Faugeras et al., 1998].

After control points are established, the photographs of the project area are taken. Digital, metric film-based and standard film cameras can be used to acquire the photographs.

4.2.2 Digital Photogrammetry Equipment

This section looks at digital photogrammetric equipment and the next at digital photogrammetric processes.

Workstations

A Digital Photogrammetry Workstation (DPW) is a high performance CPU used in the field of digital photogrammetry, with appropriate software, high resolution graphics screens, a stereo viewing capability and a three dimensional cursor, or equivalent. DPWs with SOCET SET software from Helava Leica and PhotoModeler from Eos Systems Inc. were used in this work. These systems differ greatly in cost (approximately US$70,000 vs. US$1000) as well as in 'user friendliness' as is shown below.

Although digital photogrammetry is considered less skilled than analogue photogrammetry, the software seems overwhelming to the non-photogrammetrist [Burden, 1997]. The other system components considered in this work (i.e. AutoCAD and ArcGIS/ArcView) represents extremely popular packages, which have become increasingly user friendly over the years; the 'user unfriendly' bottlenecks appear to be at the photogrammetric data capture stage.

A series of tests were devised in 1998 [Drummond *et al.*], [Burden, 1997] with HCI (Human Computer Interface) researchers from Glasgow University's Computing

Science Department, shortly before the start of the author's research period, to compare the 'user friendliness' of two digital photogrammetric systems then in use in Glasgow University. These were SOCET SET and DMS (from the University of Georgia). The main finding in these tests was that the actual processing time (and their differences) was insignificant, but that the different time taken to interact with the system was noteworthy (particularly for a novice user) and was an indication of 'user friendliness'. In the original tests several experienced and inexperienced users were monitored (1 expert for each of SOCET and DMS, 4 novices for SOCET and 2 novices for PMP). The DMS tests were repeated, for this investigation, with PhotoModeler (PMP), with three users – one experienced and two novices. The tests were based on five more or less equivalent steps (1-5) and two which were so different they could not be compared (6,7). Results are given in Table 4.1.

TABLE 4.1

Execution Times for Orthophoto Production

	Step	**Execution Times**			
		SOCET		PMP	
		Expert (1)	Novice (4)	Expert (1)	Novice (2)
1.	Create Project	3' 00"	2' 48"	4' 00	4' 45"
2.	Import Imagery	5' 02"	11' 53"	1' 00	2' 15"
3.	Interior Orientation	14' 36"	14' 05"	0' 48	1' 30"
4.	Exterior Orientation	15' 34"	35' 00"	10' 35	15' 30"
5.	Normalise	2' 43"	3' 44"	0' 57	1' 20"
6.	Surface Modelling	10' 28"	12' 33"	5' 30	6' 00"
7.	Orthophoto Creation	3' 00"	3' 08"	5' 29	6' 30"
	TOTAL	**54' 23"**	**83' 11"**	**28' 19"**	**37' 50"**

Considering these results, the anomalous finding that the expert is slower in creating a project (STEP 1) and executing interior orientation (STEP 3), when working with SOCET SET, than the novice, can be explained by the fact that the expert will know (perhaps from bitter experience!) that these steps have to be carried out very carefully indeed - in order not to loose data and to get good interior orientation residuals.

Overall the time taken to execute steps 1-5 in SOCET is much greater than in PMP and there is less difference between the novice and the expert for PMP than SOCET. Thus PMP can be seen to be both much easier to use and easier to learn than SOCET. The main difference is in the time taken for interior and exterior orientation. PMP does not require the measurement of fiducials, thus speeding up interior orientation. Exterior orientation (control pointing) requires fewer steps in PMP, thus there is less for the novice to learn, than in SOCET; the time difference for the experienced user may be about five minutes. Grid based processing for the surface modelling was used in SOCET and involves much more computation than the TIN based surface modelling in PMP. But surface modelling in SOCET requires little interaction to process millions of points while PMP requires (perhaps a few dozen) points to be selected by the user and the number of selected points will affect PMP's timings.

SOCET has been designed for extensive mapping projects using aerial or spaceborne imagery and minimal ground control. Even after several months of working with SOCET the author remained disappointed by its 'user unfriendliness'. For a professional (such as a museum technician) who is only an occasional photogrammetrist the user friendliness of PMP and its applicability to small terrain objects seems to have much to recommend it.

Cameras

Using digital photogrammetry makes the application of non-metric cameras more possible; corrections for image degradation can be easily carried out. Both metric and non-metric cameras have been used in this work. Placing the camera on a tripod makes it more stable, thus more precise. If camera stations have been planned beforehand, then setting up a tripod at the camera station may be more reliable than just positioning a hand held camera in more-or-less the right location. If tilt angles are known at the time of photography, these can be used as approximate values for tilts in subsequent iterative determinations.

It is necessary to define the internal geometry of cameras. Metric cameras tend to have more information available. Two calibration reports which have been available for this investigation: for the UMK 10/1318 and for the Kodak DC260 are compared in TABLE 4.2. For other camera types, less information is available, so self-calibration (on the job calibration) becomes a necessity.

TABLE 4.2: Calibration Parameters: UMK 10/1318 and Kodak DC260

Camera	Format	Distortion Parameters	Lens distortion values	
			r (mm)	Δr (μ)
Zeiss UMK 10/1318	**Image Format** Width = 129 mm Height = 179 mm **Principal Point Offset** x_0 = 0.008 mm y_0 = 0.004 mm **Principal Distance** c_k = 98.903 mm	a_1 = -2.07346 a_2 = 0.89268 a_3 = -0.01180 a_4 = 0.00000	10	0
			20	0
			30	0
			40	1
			50	1
			60	0
			70	-3
Kodak DC260	**Image Format** Width = 13.729 mm Height = 9.11 mm **Principal Point Offset** Unknown **Principal Distance** c_k = 28.3892 mm	k_1 = 0.0000958200 k_2 = 0.0000003593	1	0.113
			2	-0.035
			3	-0.053
			4	-0.063
			5	0.015
			6	0.275
			7	0.232

There is a wide range of cameras for capturing data for terrestrial photogrammetry purposes. Cameras can be classified into three categories: metric film, non-metric film and digital cameras. Usually, a metric camera is film-based (or rarely a digital camera) and is designed specifically for metrology, and a non-metric camera has other design goals.

Large-format cameras can have many problems with film flatness. In metric cameras platens hold film flat during exposure. In a good 35mm camera, the film will be relatively flat but might be a little bit deformed. Typically, CCDs have better flatness characteristics than film.

The position of the perspective centre of the camera at the time of exposure is given in the X,Y,Z ground units of the project. For object measurement, the software used for processing requires to know the exact position of the image plane throughout the exposure time. With a film-based camera, the corners of the frame are visible on the image and therefore are referenced in the software. PhotoModeler requires the position of the imaging medium (film or CCD) relative to the camera lens during the exposure time. With a digital camera or CCD video camera, the imaging sensor is fixed onto the body of the camera and as long as the lens position is fixed to the body, a rigid and highly repeatable means of locating any individual CCD pixel in the lens/camera/media system is available.

Each photograph has a rectangular border, which is the image of the rectangular frame in the camera body between the lens and the film. In a 35mm camera this frame is approximately 36mm by 24mm. This frame is part of the camera body and hence does not move relative to the lens from exposure to exposure.

Metric Film Cameras

Metric film cameras are frame cameras designed to provide extremely high geometric quality images, and are sometimes called "mapping cameras". They employ a low distortion lens system held in a fixed position relative to the plane of the film. The requirements of metric photography lead to a fixed focal length, known lens distortion and known offset of the principle point's position. Application software has to provide correction for these distortions/offsets. Photographs from those cameras will need to be scanned, for digital photogrammetry. Generally, the first generation of film, the negative, is scanned on a special, geometrically calibrated photogrammetric scanner at high resolution. For metric cameras, the interior orientation process involves establishing certain properties, namely: the lens focal length; the principal point offsets; the radial lens distortion parameters; and, the fiducial coordinates, of the photograph being processed. This information can be found on the camera's calibration certificate, but the correspondence between the image coordinates of the fiducials and their calibrated coordinates must be established for each photograph. The calibration information is used in the subsequent data processing to remove distortion associated with internal sensor characteristics such as radial lens distortion [Fraser, 1997], in transforming the scanner coordinate system to the photo-coordinate system and in subsequent processing where photo-coordinates are further transformed. Processing the camera calibration in SOCET SET is dealt with when the information about control points, fiducial marks, scale distance and camera parameters are inserted into the software.

FIGURE 4.2

UMK 10/1318 Zeiss Jena Camera

(Source: Instruction Manual of Photographic System, Universal Surveying Camera UMK 10/1318, Carl Zeiss Jena)

Of metric cameras, the Universal Surveying Camera UMK10/1318 Zeiss Jena (Figure 4.2) was used in this work. The UMK10/1318 camera is a metric camera with a picture format of 120mm x 166mm and uses a non-standard film width of 190mm. There are four fiducial marks, middle bottom, middle top, middle left and middle right. The focal length of UMK series cameras is about 100mm, with a focus setting from ∞ to 1.4 m.

Non-metric Film Cameras

Non-metric film cameras record image detail without the geometric fidelity of mapping cameras. A good quality non-metric film camera could be similar to a metric film camera, except for the lack of fiducial marks and an approved camera calibration certificate. These control the interior orientation of the photogrammetric model. Having enough ground control points, modern triangulation software will calculate the necessary camera properties, and allow precise photogrammetric measurements to be made. Therefore, the much lower cost of these cameras (compared with metric cameras) makes them attractive to many organisations given their utility for stereo modelling and photogrammetry [Fryer, 1996]. The disadvantages of non-metric film cameras are that modifications (software or hardware) for a lack of film flattening and the definition of a reference for the image coordinate system need to be made.

Digital Cameras

As with the film cameras, for metric or non-metric digital cameras there is a requirement to define the camera properties. These are in this case: the lens focal length; the principal point offsets; the radial lens distortion; and, the x and y pixel dimensions of the CCD (necessary for digital or video cameras).

Self-calibration software should solve for all of these camera properties.

Four non-metric digital cameras were used in this work: the Kodak DC260 (1.5 megapixels), the Kodak DC4800 (3 megapixels), the Sony DSC-F828 (8 megapixels) and the FUJIFILM A920 (9 megapixels). These cameras became available at different stages in the work reported in this thesis, each having a higher resolution than its predecessor, which was the reason for the acquisition. The simple assumption that the higher the resolution the better can be adopted in this work as processing time is barely affected by the increased resolution, especially if one considers that a scanned aerial photograph undergoing photogrammetric processing may have 400 megapixels

For two of the cameras used in this project (UMK 10/1318 Zeiss, Kodak DC260) the complete set of interior orientation parameters, determined by a test-field calibration is presented in Table 4.2. The other cameras (Kodak DC4800, Sony DSC-F828 and FujiFilm A920) were used with the self-calibration software included in the Photo Modeller Program (PMP).

No metric digital camera has been considered in this work.

4.2.3 Digital Photogrammetric Processes

A combination of photographs and (possibly digital) sketches are needed to make a comprehensive record of a cultural monument for input to a spatial information system. The photographic coverage required differs from one object to another, depending on the personnel and equipment available and on the nature of the monument. Efforts should concentrate on retrieving a maximum amount of information in a minimum amount of time. Sketches are particularly important for the unambiguous location of non-targeted control points. The physical targets of targeted points should be labelled to avoid ambiguity in the photographs.

The parameters of exterior orientation can be established from points with known object coordinates (control points) and points with unknown object coordinates located in two or more images (tie points). Ideally control points and tie points are targeted when high accuracy is needed.

It has been experienced that if a point appears in two photographs but its position in one photograph can only be approximately determined, the resulting 3-D coordinates will have low accuracy and will probably be incorrectly placed in 3-D space. If there are too many points marked in this manner, other points marked precisely will be nevertheless affected and the whole model will become inaccurate.

Terrestrial Photos

Hundreds of historical buildings and cultural objects are destroyed every year and the interior decoration of more is being lost or covered over, reinforcing the case for the systematic recording of cultural monuments.

Surveying photo control points can be accomplished by using either a theodolite (one second), tape measure with angle intersection from two ground stations, calculating the 3-D coordinates of the control points, or by using a reflectorless total station. The most challenging task at this stage is to recognise points that can be identified from the ground stations and found on the photography. Points can be divided into targeted and untargeted points. Features from the rich textural details often found on cultural objects may be selected as untargeted points. But coordinate information can come from other source such as from scaling a paper drawing. Additional information on size, condition, materials, etc. is captured manually, with the information later added to the database.

Most architectural photography uses natural light. A reasonably diffuse quite strong light, as seen on a cloudy summer day, is ideal for most sites. Low levels of illumination lead to long exposure times, but are not as troublesome as bright sunlight, which casts strong shadows in which it is difficult to identify much detail. This can be removed with filters, but the results are often flat. On many photographs it is essential to get as great a depth of field as possible so that points across the picture are sharply in focus. Closing down the aperture and lengthening the exposure time achieves this. Where an overall picture is needed, the photograph can be taken from the air – such as from a hydraulic lift, providing a near vertical photograph. Vertical photographs are not only useful to give a general view of the site but also form a basis for making maps or plans of the general layout.

Terrestrial photographs are a significant part of a cultural monument's permanent record. Good records will describe every part of the monument, each section, all features and any evidence of destruction and rebuilding. It is important to show the object from all angles, picturing the object and elevation of the site itself, as well as shots from as many view points and distances as possible.

When considering the equipment needed, too many variables exist to recommend particular equipment as universally suitable, to the exclusion of all else. The choice of equipment will largely depend upon experience, the location of the object, length of time on the site, etc. Relatively small viewing areas may be more difficult to work in.

In the projects investigated in this thesis, when using the metric camera, most of the photos were made with a horizontal base in which the camera axes were horizontal and nearly perpendicular to the object, while the axes were vertical when a ceiling was photographed from inside the object, for example. The photos were developed and examined on the site, and the pictures of poor quality repeated. At the same time it was checked to see whether the necessary overlaps between the pairs were achieved; if needed, additional photos were taken.

Digital Photos

A digital still or video camera captures image information as electromagnetic radiation of certain wavelengths on a light sensitive computer chip, a CCD. The chip replaces the film and converts the image information into a numerical form representing colour and density. To produce a visual image on an output device such as a screen or printer software will convert this numerical information. Since the original image consists only of numerical data, exact copies can be made and then further images can be made from these copies. At each stage of copying there is no systematic loss of image quality between generations (some minimal random image loss may arise). If all information is stored on the correct media, there should be no deterioration over time.

Scanning of Terrestrial Photography

Scanners take an original photograph and convert it into a series of digits to provide image data. When a film-based camera is used, there are four different scanning technologies available:

- 35mm roll film scanners (e.g. PhotoCD);
- Flat bed scanners;
- Hand held scanners; and
- Drum scanners.

All the above scanners involve mechanically scanning a sensor or mechanically shifting the film. All scanners add further distortion to the image captured on film. Making mechanical movements precise can be expensive and many consumer-grade scanners are not very precise.

The PhotoCD format may be valuable because a roll of 35mm film can be scanned inexpensively. The other three scanner types can scan between 100 and 3000 dots per inch. A good office flatbed scanner can capture up to 600 dots per inch. If one prints the film first and then blows-up the negative to scan it, a very high resolution results.

In the projects investigated in this work and using the UMK camera, digital image data were obtained by scanning the original developed film on the VEXCEL VX-4000 scanner (of the Bo'ness, West Lothian company then known as SDS, now known as DSM). Digital image data were scanned at a pixel size of 15 micrometers (equalling about .7 mm ground distance). Scanned digital image data can be directly exported to a DPW or put on CD, the latter being chosen for the work reported in this thesis.

4.2.4 Producing the Relief Model

As noted before, ground control points are obtained through land surveying, or other high quality sources. As well as being used to obtain the orientation parameters of the photographs, the ground control provides a frame of reference and ensures the planimetric coordinates and heights are related to an established origin and datum, respectively. Once these data from two or more overlapping images are corrected for known distortions, a three-dimensional mathematical model of the surface of the object is created, by image matching.

Image correlation is a technique to obtain the conjugate points of an affiliated image by matching it to a master image through searching for the maximum correlation coefficient. Image correlation is applied to stereo images to obtain x-parallax and hence the z coordinate of a pixel, for DEM creation. There are several different correlation strategies which can be applied, most proprietary. The correlation strategies found to be most successful on cultural objects used in this investigation are: *Flatest3* (applied in SOCET SET) and *Adopted* (applied in Photomodeller).

The effectiveness of the correlation is influenced by the nature of the imaged surface (its tonal variability, its smoothness, etc.). As will be seen in the next chapter, a significant problem with the St. Avit investigation was the homogeneity of the walls across large areas, making image matching difficult. (A return visit to St. Avit with appropriate lighting equipment to introduce a 'speckled' effect was precluded, due to funding constraints). The final orthorectification of the original images is achieved one picture element (pixel) at a time by using the digital surface model to work out each pixel's correct position and an orthophoto (from which differential scale and displacement effects of tilt and relief are removed) is produced after resampling the displacement corrected model.

Since an orthophoto has a uniform scale, it is possible to measure directly on it like on maps or architectural plans. An orthophoto may serve as a base plan onto which other information may be overlaid. A digital orthophoto can be used on screen to collect, review, and revise other digital data (such as the edges of architectural features), or to link ('hotlink') to other data sets.

A stereomate of a building's façade can be produced from a façade's orthophoto, which has the displacement effects of relief reintroduced. If the orthophoto and the stereomate are viewed simultaneously then this better enables the identification of architecturally significant features, and the extraction of their 3-D coordinates. This extraction is achieved by identifying, on screen, the architecturally/archaeologically relevant pixels (points) in the orthophoto. SOCET produces stereomates; PMP does not.

The screen coordinates are transformed, on the fly, to their LCS or WCS coordinates to provide X,Y coordinates for the selected point. Having identified the X,Y values of the point, its z value is extracted (again on the fly) from the relevant digital surface model. Thus the X,Y and z coordinates of a point are found, and can be exported to an appropriate 3-D coordinate file.

To extract contours from the digital surface model and add that information to the orthophoto is a quick additional process, which nevertheless helps in understanding orthophotos of building detail. Digital surface model products available for further work related to the management of cultural monuments are:

- digital surface models in virtually any format; and,
- Z-value contours as separate TIF images and DXF files (which can be plotted as an overlay on the subsequent orthophoto in the A/AIS).

For buildings with either extensive or complex façades (or both), to create an orthoimage, more than one single stereopair is needed, per façade. In this case, the orthorectification must be done in several pieces, and the results need mosaicing.

4.3 GIS Software Applied to Modelling Cultural Objects

According to the NCGIA [1987], GIS can be defined as "a system of hardware, software and procedures designed to support the capture, management, manipulation, analysis, modelling and display of spatially referenced data for solving complex planning and management problems". The model is usually built from a series of 2-dimensional layers, each layer being associated with a theme. The attributes of the objects represented in each layer are stored in linked database tables.

GIS is widely used by planning organisations. Part of its function is as an archiving system, but usually for maps rather than photographs. The analytical tools it provides, specifically overlay, buffering and spatial query are ideally suited to the decision support tasks of planning organisations, but other tools offered include network analysis, terrain analysis, image analysis and map publishing. GIS may be regarded as a general-purpose tool, which will need to be supported by specialist tools as necessary.

4.3.1 GIS and 3-D Representation

The idea of DEMs emerged in 1958 for computer aided road design. After ten years, it was realised that the DEM provided a terrain description appropriate for cartographic mapping, and could be considered for non-topographic surfaces as well (although in this latter case the coordinate systems need not necessarily be based on the familiar E, N, elevation system). The term Digital Elevation Model (DEM) can be used to mean the digital representation of the earth in many forms: rectangular grids or lattices, triangular networks or irregular spot heights and break lines. DEMs produced by digital photogrammetric workstations are usually digital representations of the elevation of the land (Z value) at specified regular X,Y locations (Easting and Nothing or longitude and latitude). In terrestrial photography the X,Y coordinates may represent the horizontal and vertical axes of a building façade, with the Z axis in the depth field. For this reason it may be more appropriate to refer to a Digital Surface Model (DSM) rather than a Digital Elevation Model. PhotoModeler, by generating the X,Y,Z coordinates of feature points provides input for a TIN (triangular irregular network) DEM (or DSM). 3-D models rendered from DEM data can be extremely useful and adaptable [Hilgers *et al.*, 1998]. The term DEM and Digital Surface Model are both used in this work.

A DEM may be used in the generation of 3-D graphics displaying slope, aspect (direction of slope), profiles between selected points and generating further surface representations such as curvature and rate of change of slope. In addition, DEMs can be used in combination with other raster graphics (e.g. orthophotos) for improved visualisation.

Automatic generation of DEMs may use various sources of information, which are provided digitally and have an adequate compact description of the objects. Whether grid or TIN, DEM is a surface model of triangular or rectangular faces. In practice this means the modelled surface can have no hollows, holes or tunnels in it, such as created by windows, passages or the intricacies of carving or sculpture. This presents a basic difference with the 3-D modelling of bodies in CAD systems. DEMs can model the façades of bodies only, but this may be adequate, if every façade is reduced to its component facets and every facet is modelled. The main problem of data acquisition for DEMs is how densely the observed points should be captured in order to give the desired accuracy, and this relates to the smoothness or roughness of the surface. A number of other effects are clearly important, such as the accuracy of measured points, the spacing and the interpolation method used (if any) [Gargantini, 1982].

In future geo-information systems with 3-D databases, spatial objects like cultural monuments and other man made constructions will need to be truly described in three-dimensions. Although having been a research topic for some thirty years, 3-D GIS is still only supported in high-end or experimental systems [Smith and Friedman, 2004]. 3-D descriptions of buildings, are obviously time consuming to generate, unless e.g. a "building database" can be automatically populated from other sources (such as images). At the moment the automatic identification and extraction of building detail by digital image processing has not been generally solved, but, given buildings' standardised but distinctive 3-D characteristics, it can be assumed that knowledge-based methods will emerge.

It is common now to be able to drape a layer (or fusions of layers) on to a digital terrain model using GIS terrain analysis tools, but this solution is most suited to topographic representation. Standard Geographic Information Systems currently support both grid and Triangulated Irregular Networks (TIN) based terrain modelling, but the draping usually involves the TIN model. Although 3-D Geographic

Information Systems are found in the research environment and in 'high-end' systems, standard GIS products do not model the world in 3-D. The draping tools, which can be used, are considered 2 ½ D.

Geometric modelling tools in established GIS systems provide a means for the virtual reconstruction of entities. This involves the representation of the real world object as a collection of points, lines, polygons but, above all, facets. Representing a real world object, such as a building as a set of facets allows for the representation of overhangs, etc. The geometry is defined by, at least, two lists: all points composing an entity and ordered lists describing the boundaries bordering its facets. The model created can be presented as a set of facets and each facet as a set of vertices.

The purpose of 3-D geometric modelling is to enable a remote definition of real entities, thus aiding their reconstruction, maintenance, recognition etc. Three-dimensional facets in computer systems, as Anand [1993] has noted, can be modelled as 3-D polygonal surface meshes. If these polygonal surface meshes are reduced to triangles, the TIN approach can represent facets. The TIN approach to 3-D surface representation is a standard GIS function, but to do this on the basis of a set of facets describing a real world entity is non-standard.

3-D data for the generation of the geometric representations in GIS or CAD can be acquired by digital photogrammetry. This requires automated image matching, usually area based. The approach has been successful with terrain images taken from aerial platforms, but architectural objects have significant surface discontinuities (such as caused by overhangs) resulting in photographic occlusions, which affect the image matching. If the matching is done facet by facet, then it seems matching is strengthened. In architectural and archaeological work the 3D data needed for modelling should be gathered in this way.

4.3.2 GIS Representation of Non-geometric Attributes

Considering the digital representation of the non-geometric aspects of a model, these require an organisation of attributes. Attributes of cultural features that we might be interested in include construction and historic details (materials, year of construction, purpose, etc.), which can be stored in linked database tables and accessed through 'query'. Other files, such as images or text (for example containing commercial or biographical details of architects), can be linked to any model through features such as ArcView's 'hotlink'. However, an important requirement in this application area is 'future measurement'. For example, the lintel of the window on a historic building might get broken. Future measurements would be needed for its restoration. Retaining the orthoimage and its linked three-dimensional surface model, from which the three-dimensional coordinates used to create the historic object's model were captured, can support this future measurement. The orthoimage and surface model can be retained in linked files. Alternatively, the orthoimage could actually become part of the model, providing the rendering, but also a facility for future measurement. Examples are provided in figures 4.3 and 4.4.

FIGURE 4.3

South Face of the Gilbert Scott Building with a Layer of Images (Labelled 'Hotpics' in the ArcView Menu) including a Medallion, Providing Further Detail

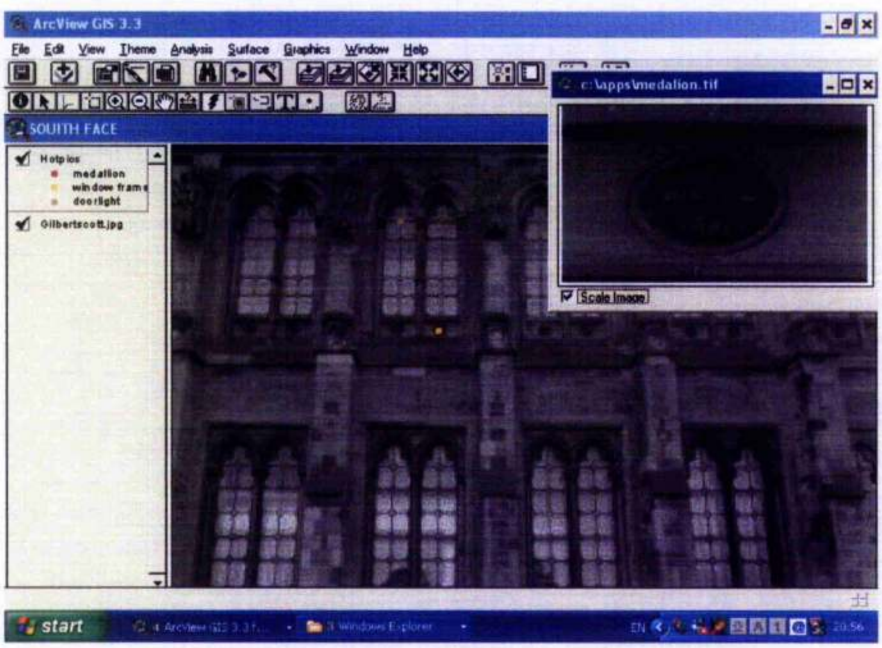


Figure 4.3 shows the hotlink to architectural detail. When *selected* magenta coloured 'hotspot' shows *bright* yellow and links to a large-scale photo of a medallion in the stonework. In Figure 4.4, the orthophoto is imported into the GIS via an application 'SOCET_hotlink' for GIS on-screen digitising.

4.3.3 3-D Model of a Building using Off-the-shelf GIS; Simulated Examples

PC ArcView (predecessor of ESRI's ArcGIS) is a low-cost standard off the shelf GIS, developed by the corporation ESRI. If used for 3-D modelling it requires that a model be constructed from facets. With regard to modelling three-dimensional objects, ArcView is two-and-half dimensional. Without extra development, using ArcView its 2 ½ D approach to 3-D modelling introduces constraints or requirements, which are those listed below.

1. The direction of the LCS (Local Coordinate System) axes, with the origin below and behind the object forces all object point coordinates to be positive.
2. The XY plane of the LCS being approximately, but not exactly, parallel to one of the building facets, in the FIG 4.5 case the south facet. (This requirement arises because each facet must be described by a single well-formed polygon in the XY plane, i.e. no intersections).
3. Each facet is described by at least 4 object points (a requirement of the chosen GIS when 3-D shape files are being created using a TIN).
4. There are no two points have the same X,Y coordinates but different Z coordinates (a requirement of the chosen GIS arising because we are exploiting the system's 2½ D surface modelling functionality to produce 3-D models).

These requirements support the B-rep approach as demonstrated in the simulated building of Figure 4.5 showing the coordinate system for the integrated GIS-Photogrammetry tool. The origin of the local coordinate system (LCS) is North West of the north building face, below the level of the building base. The XY plane is nearly but not exactly parallel to a face (south face) and south of it, ensuring all building point coordinate triplets are positive.

FIGURE 4.4

Orthophoto of a Station Building, being Measured/Digitised

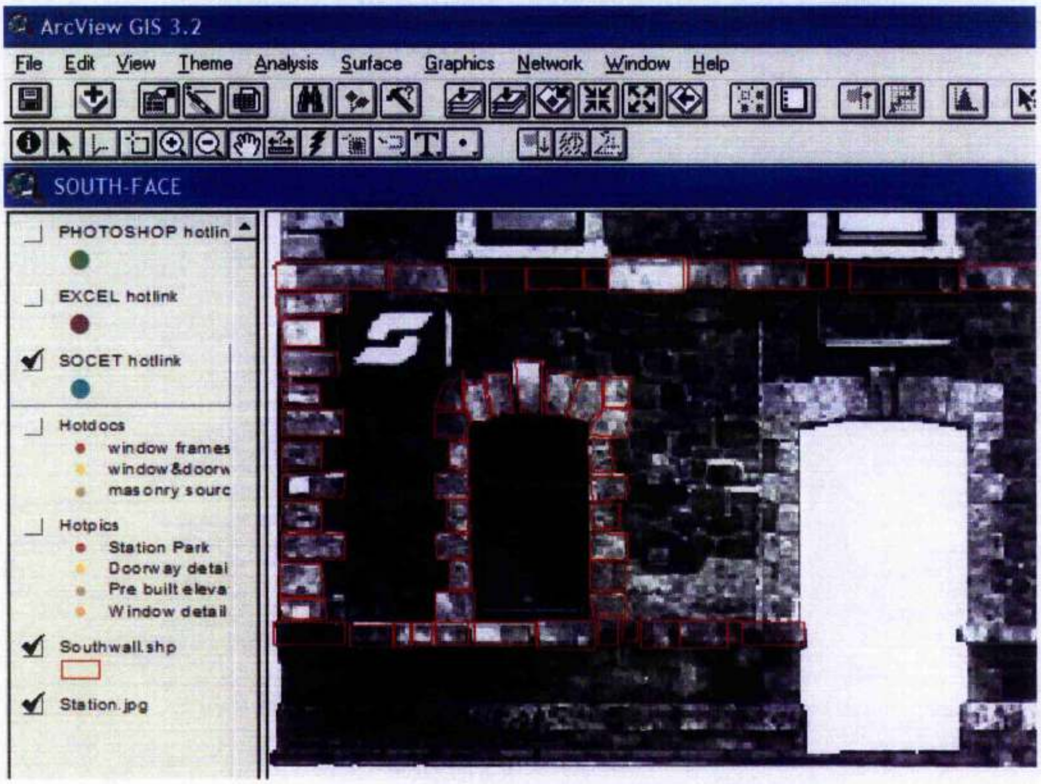
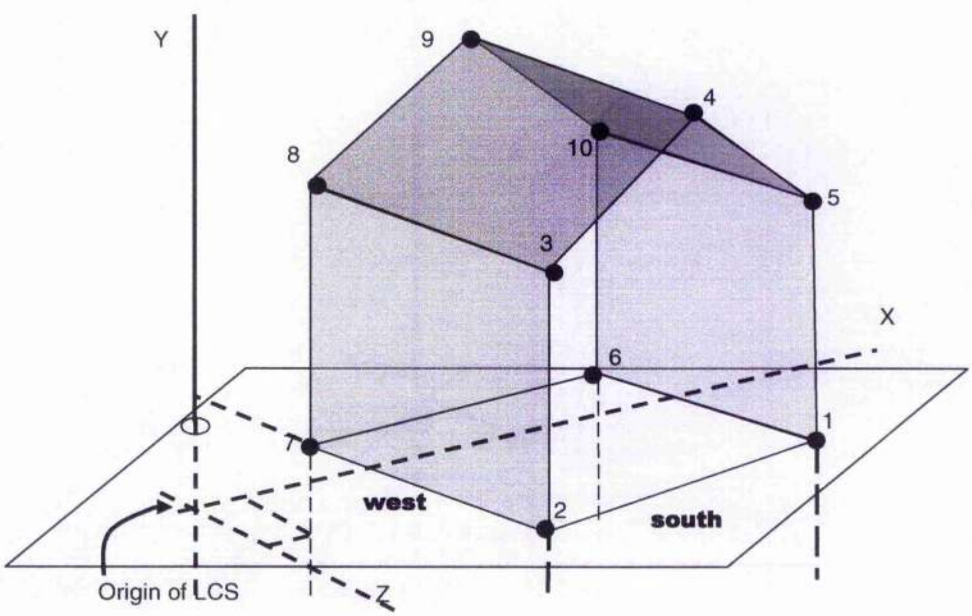


FIGURE 4.5

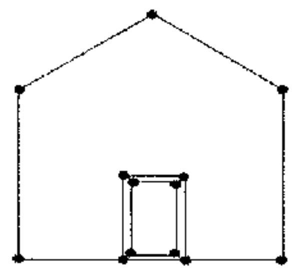
The Local Coordinate System for a Modelled Building



In the approach suggested here, based on an ESRI GIS environment (ArcView), the cultural object is represented by a data structure giving information about each of the object's facets, using edges and vertices – see Figure 4.6 as an example. This is the B-rep approach in its simplest form. The object must be reduced to planar faces (facets). All vertices must be represented by positve coordinates, in a right-handed Cartesian coordinate system, thus its origin must be below and behind the building. The coordinates can be provided by photogrammetry.

FIGURE 4.6

The B-rep Model of the Façade of a Building Showing Six Facets (front face of building, door and four porch facets)



The topological model also represents a subdivision into facets and enables a more efficient implementation of operations that require "connectedness" information, such as efficient spatial data organization, spatial analysis, spatial query, spatial reasoning and consistency testing [Guo, 1996]. Figures 4.7 and 4.8 show the facet based 3-D model of a building in the ArcView environment. Figure 4.9 illustrates apertures in a 3-D model, as supported by ArcView. These can be rotated (as shown between FIGURES 4.7 and 4.8) demonstrating the effectiveness of 3-D modelling in this ESRI environment.

FIGURE 4.7

A 3-D Building Model A, using ArcView

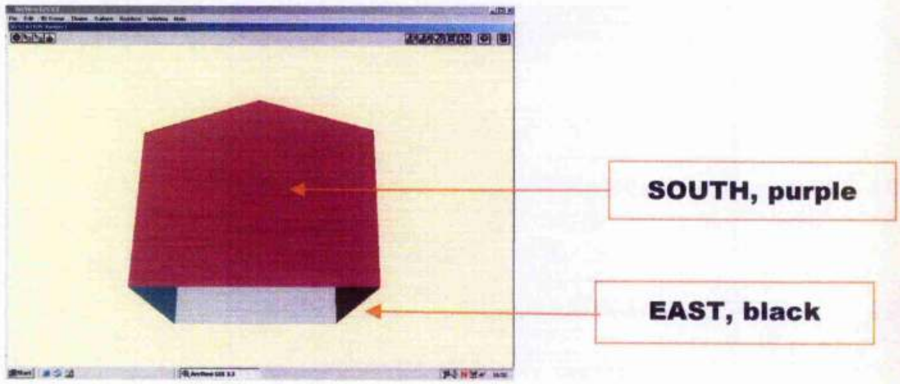


FIGURE 4.8

A 3-D Building Model A, Rotated

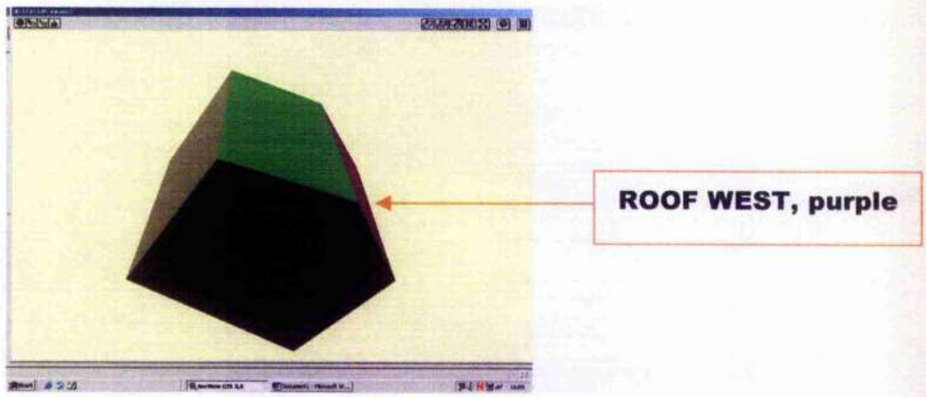
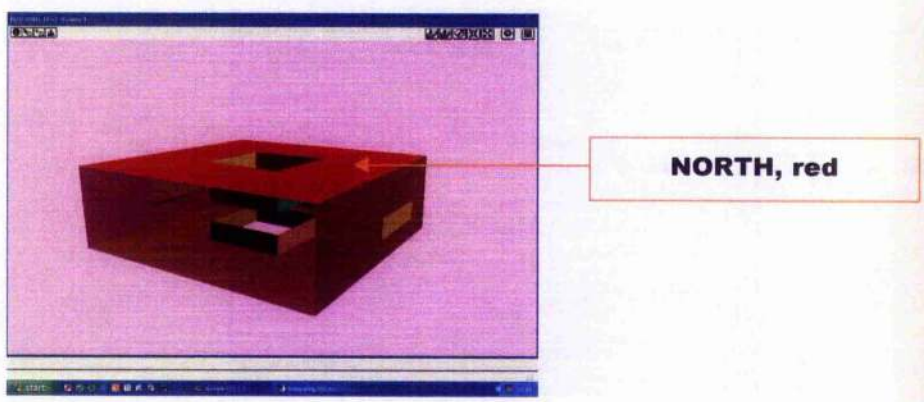


FIGURE 4.9

3-D Building Model B, Showing Apertures through the Base



In this approach geometric transformations can convert the positions of points on a 2-D photograph to the 3-D coordinates used to model the 3-D object. But thereafter, once the database has been created, objects are viewed on a screen, and probably one of the most basic 2-D planes (i.e. *xy*, *xz* or *yz*). The algorithms for performing basic computer graphics operations such as geometric transformations must also exist in a form extended to deal with 3-D objects [Samet, 1990]. Also see Appendix C.

4.4 Visualisation

Visualisation supports interaction between data and users, based around a computer graphics environment. It involves the production of scenes or graphical representations of data. A scene may attempt to render data as it might appear to a human observer or alternatively, transform data values, which do not have a true visual appearance into a pictorial representation, aiding understanding. A scene is composed of a number of primitive graphical objects such as a point, a line, an arrow, a mesh, etc.

Visualisation displays data for human interpretation. Visualisation is based on the human ability to impose order and identify patterns. An outgrowth of statistical analysis, visualisation is now used in a variety of disciplines. It has strongly influenced all forms of data analysis and the techniques are beginning to be incorporated in cartography, hence GIS. Important elements of the visualisation interface are interactivity and animation [Raper, 2000].

The visualisation environment allows a user to symbolise data. In order to ensure that visualisation achieves its goal, the data should be encoded with the appropriate visual attributes bearing in mind the perception signals of these attributes. An obvious use of visualisation is to enable 3-D models to be constructed and viewed.

Considering the Internet, information received at a user site can be visualised either in an HTML browser (text, 2-D graphics, etc.) or in a Virtual Reality Modelling Language (VRML) browser (text, 3-D graphics). VRML is particularly used to visualise constructed objects, as this file format has been designed for visualisation, navigation through and exploration of 3-D models on the Internet. Models, which are represented in this language, can be viewed on any computer-monitor by web-browsers extended with virtual reality plug-ins, or by stand-alone applications. Using such browsers, users can navigate through a 3-D model in near real time, improving perception. The VRML file is created during the process of reconstructing a 3-D object [Suveg and Vosselman, 2000]. VRML is an open format that has become popular because of its suitability for publishing 3-D data on the World Wide Web. For this reason there is much software available that can handle VRML.

Among the rendering languages, VRML is a high-level language for scene modelling and provides not only techniques and methods for rendering but also dynamic displays. The dynamic displays range from techniques to play animation to deleting user actions and observing the consequent reaction of objects. In this aspect, the methods provided by the language can be classified as methods for scene design (geometry, lights, textures, etc.) and methods to introduce dynamics. The user can interact with the 3-D model inside the VRML browser, fly over, walk through, examine and at the same time browse text information in the HTML browser. This can be displayed at the screen in several ways: one window with several frames, several new windows or combinations of them. The individual windows provide the user with more freedom to resize and adjust observed models.

In the case of archaeological and architectural sites, 3-D visualization could be used to ensure a better understanding of a site. A high quality of visualisation may be achieved through using orthophoto products to render façades. PhotoModeler software supports the production of orthoimages and supports a user's interactive examination and visualisation of the data. This is investigated in the Anobanini and Hunter Memorial projects of the next chapter.

The visualisation of an object that has not been decomposed into geometric shapes requires structuring as a DEM/TIN model which can be rendered. For example the model may be draped by an appropriate orthoimage, or rendered using an appropriate set of hues or patterns. This is necessary, for example, when one wants to visualise cultural objects, without decomposing them into geometric shapes. The creation of

DEM/TIN models requires an automated image matching step for which the presence of texture is essential. The absence of adequate texture created problems with the St.Avit data (see Chapter 6).

If an object's visualisation requires geometrical shapes, these have to be fitted through a set of neighbouring points, which together build-up into an object or a part of it. This process converts the set of x, y and z coordinates into a restricted set of shapes. Even when auto-segmentation tools are used, much manual processing is still required for this.

4.5 Rendering

Rendering is the process of generating an image from a 3-D model, by means of computer programs. The model is a description of three-dimensional objects containing geometry, viewpoint, textural, lighting and shading information. One possible result of rendering is to have a recognisable visualisation. This will ease the task of the user who needs, perhaps, to measure the model after a catastrophe. The aim of rendering a 3-D image is for a model to look either visually interesting or realistic, or both. Since computer graphics' early days, there has been an interest in better realism in the rendering of 3-D objects. This requires computing how each pixel should look. Much of the process of creating a final 3-D image is based on a shading model that deals with polygonal objects [Watt, 1993]. It attempts to model how light that originates from light sources would act together with objects in a scene. Due to practical limitations, one usually does not try to simulate all of the physical principles having to do with the scattering and reflection of light. These principles are quite complicated and lead to very slow running programs. However, a number of models have been invented that use approximations and still do a good job producing various levels of realism.

In order to show the issues involved, it is necessary to describe a hierarchy of techniques that provide increasing levels of realism, Then, how each techniques is incorporated into an application is examined.

At the bottom of the hierarchy, offering the lowest level of realism is a wire-frame rendering. Wire-frame views of an object can be drawn very rapidly, but are difficult to interpret, particularly if several objects in a scene overlap. Realism is significantly enhanced when the faces of objects are filled with some chosen colour(s) and surfaces that should be hidden are removed, but pictures rendered this way still do not give the impression of objects residing in a scene, illuminated by light sources. Figure 4.10 shows a 3-D shape (a jewellery case) as a wire-frame. With this technique, in which the edges are only drawn, it can be difficult to see "what is what".

FIGURE 4.10

A Wire-frame Rendering of a Jewellery Case

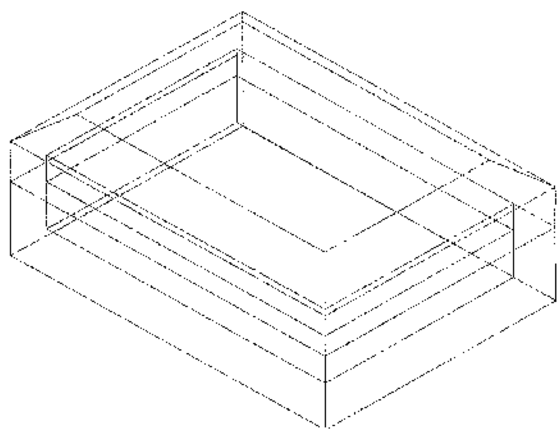
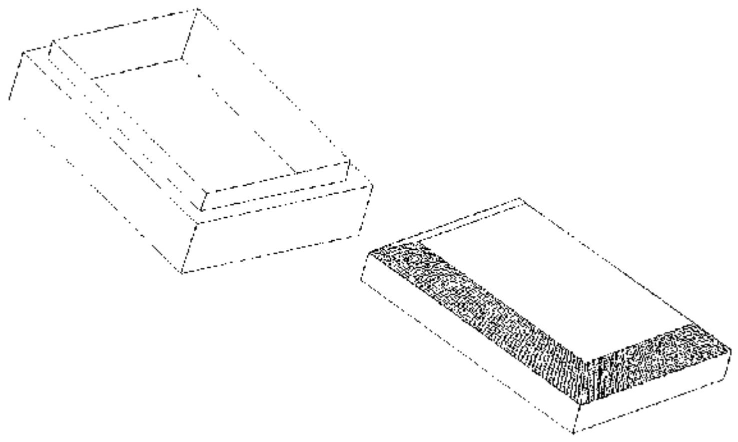


Figure 4.11 makes a significant improvement by not drawing any edges that lie behind a face. It is called a "wire-frame with hidden surface removal" rendering or "hidden line removal". The lid of jewellery case is now drawn disjointedly.

FIGURE 4.11

Wire-frame Views with Hidden Surfaces Removed from the Jewellery Case (with lid separated)



Even though only edges are drawn, the objects look solid and it is easy to tell where one section stops and the next begin. It is noted that some edges simply end suddenly as they slip behind a face, while others are completely absent.

The next step in the hierarchy produces pictures in which objects appear to be "in a scene", illuminated by some light sources. Different parts of the object reflect different amounts of light, depending on the properties of the surfaces involved and on the positions of the light sources and the viewpoint. This effect requires computing the brightness or colour of each fragment rather than having the user choose it. The computation uses a shading model, which determines the proper amount of light that is reflected from each fragment.

A rendering function calculates shading based on the surface normal of the object being rendered. A surface normal is a vector that is perpendicular to each point on a surface. Most 3-D programs have a function that allows a programmer to view a surface's normal, which are represented by small lines in the view-port. The surface normal is usually the most important factor in determining diffuse shading [Goral et al., 1984]. The line where diffuse shading from a light stops to illuminate the surface is called the terminator. Increasing the brightness of a light or increasing the diffuse setting of a shader can make the terminator into a more visible and abrupt transition.

The depth buffer is effectively an extra frame store and a very fast hardware solution to the problem of rendering pictures of 3-D objects [Parent, 2002]. Considering an ordinary computer display, typically, 24 bits represent each pixel or dot on the screen, which means that there are eight bits each for each of red, green and blue. The display electronics scans the memory at the same speed as the electron beams are scanning across the screen and the numbers representing the red, green and blue are used to control the beam currents and making a picture. It is when the processor puts new numbers in the memory, that the picture changes. For each pixel on the screen, it records how far away the real object is from the viewpoint that the pixel is representing.

Another method to enhance the realism of a 3-D object is shadow construction and texture mapping. The technique of painting shadows as a texture works for shadows that are cast onto a flat surface by a point light source. With texturing, an object can appear to be made of some material such as brick, wood or other materials that can be attached to surfaces. Texturing deals with the surfaces in order to achieve greater realism. It is done by adding surface texture to the various faces of a mesh object. So-called mapped textures will be shaped from photographs by mixing various overlapped views of the object using pixel blending [Parnet, 2002]. Mapped textures are particularly prone to aliasing (aliasing is an inherent property of raster displays, being the actual revelation, to the viewer, of the raster structure). In addition, the texture itself is usually defined as a raster-map and there is often a complex interference (i.e. a moiré pattern) between pixels on the display and pixels in the texture map. This is the situation that can arise if an orthophoto is used to render the relevant facet of a 3-D model. In texture mapping, as Heckbert [1986] has reported, anti-aliasing is necessary.

Texture adds variation and detail to a surface that goes beyond the level of detail modelled by the geometry. Texture can be used to control many different attributes of a surface to produce different effects in purposed rendering.

A Uniform Variety (UV) map is an alternative to projecting textures through space. The UV maps are the most popular way to texture NURBS surface and are of growing importance in texturing polygon meshes [Ebert et al., 1994].

It can be seen that numerous approaches have brought texture onto 3-D models. But, obviously digital cameras can photograph textures from 3-D objects and digitise them instantly. Furthermore these same photos may form the orthophoto from which 3-D coordinates can be extracted. This was the approach adopted in the Anobanini Rock Sculpture project. It is highly likely that all the photos of an object were captured at the same time, and thus have consistent lighting. Thus using these photos (or orthophotos) to render the 3-D model is clearly likely to render to the highest level of realism.

4.6 CAD Environment

Various CAD packages are considered in this work, not only AutoCAD but also to a limited extent Intergraph Microstation. Furthermore every other geospatial package used has CAD elements in it, that is SOCET Set, PhotoModeler and ArcView. AutoCAD is the archetypal CAD package.

Drawing onto an interactive screen requires high resolution and processing speed and considerable storage capacity. Graphics packages can be divided into 2-D and 3-D packages and the user must make this fundamental choice based upon need. A 2-D package may be very capable in all respects other than to show a true 3-D representation of an object. In a 3-D package, isometric and other projections can be obtained, and the more sophisticated ones allow for the rotation of objects in space. It is assumed that cultural organisations will need to represent the objects for which they have responsibility using three-dimensional coordinates.

One of the existing packages for creating excellent 3-D modelling and rendering (and object animation), and available on a PC, is AutoDesk 3-D Studio [Greenberg and Greenberg, 1995]. After creating a 3-D model, a better representation of the spatial data can be obtained by combining the models with orthophotos, by mapping the photos onto generated surfaces. As Rodcay [1995] said, these functions should be standard in GIS, but the acquisition, manipulation and representation of 3-D graphical data still remains a challenge to designers of GIS.

In the context of architectural and other building applications CAD and GIS systems are somewhat interchangeable. CAD has presented an alternative to GIS in the fields of engineering, architecture, archaeology and surveying. CAD systems can be used to capture and translate data into a GIS format [George and Korte, 1997], although successful translating of CAD system data to a GIS format requires planning in advance. There are many organisations using CAD systems instead of GIS techniques for mapping, while other organisations that make maps or plans have a greater need for automated design and drafting functions than they do for spatial analysis and thus continue to work with CAD rather than GIS.

At the outset of the design or survey project, the surveyor, engineer or architect may be given a copy of the data for their GIS database to provide survey control or as-built data for the design. For these reasons, it is appropriate to address the issue of translating CAD data to and from a GIS site. The two primary considerations in this regard are data structure and data format.

It must be mentioned that there are differences between the structure of CAD and GIS data systems. Data elements in a CAD system are not related to one another except by reference to a common coordinate system and by "layer". There are no restrictions on placing elements in a CAD file as long as they lie within the same drawing plane or 3-D space. In a GIS system, the conventions of data topology must be applied. This places restrictions on how elements may be placed in the GIS file. Failure to follow these restrictions results in errors in file processing. Therefore, to successfully translate CAD data format to a GIS site, the CAD data must first be structured in accordance with the conventions of topology. (Otherwise, the CAD data format will produce errors in GIS processing that must be corrected after the data is translated to the GIS format [Jones et al., 1996].)

Translation uses a neutral ASCII file format to move the data between systems. This neutral file format, or *interchange format*, has been made public and two programs are needed. The first translator reads the CAD or GIS file and outputs a file in the neutral format. The second translator reads the neutral format file and translates it to the new GIS or CAD format. Because two steps are required, this process is slower than direct translation. Neutral file formats include:

- Drawing Exchange Format, DXF.
- Translating CAD to GIS Format, TCAD/GIS.
- Initial Graphics Exchange Specification, IGES.
- Map Overlay Statistical System, MOSS.
- Standard Interchange Format, SIF.
- Digital Line Graph, DLG.

4.6.1 Object Description and CAD Systems

The geometric modelling of an object is the data processing-based representation of the shapes and dimensions constituting the object. The primary function of geometric modelling is to extract an object's geometric properties. Geometric properties such as the size of structures, configuration and surface conditions, both initial and deformed conditions and geometric relations with other components are input for the subsequent design of maintenance or conservation programs.

To create an Archaeological or Architectural Information System A/AIS, additional data are required. This additional data includes alphanumerical and graphical data. Alphanumerical data consists of information such as the age of a building, construction materials and details of its last restoration. Graphical data includes images of objects, orthophoto results, 3-D modelling representation etc.

There are two approaches used by CAD systems, and specifically AutoCAD, for geometric modelling. The first is surface modelling or B-rep and the second is a solid modelling. The first requires that the object's surface is decomposed to bounded polygons. In the second instance, the model is built from the combination of primitives using CSG [Ermes et. al, 1999].

In architectural photogrammetry, surface modelling has advantages since the façades are modelled and a volumetric description with solids is not useful. In order to describe the geometry, only 3-D coordinates are assembled. This work concentrates on 3-D object modelling in architectural photogrammetry. The main influences on selecting the features whose coordinates are to be assembled are assumptions about building objects, namely that object façades are planar; this is the case with uncomplicated structures. This implies that a B-rep is a suitable type of representation for an object. But the approach becomes less manageable as the object becomes more complex, that is consists of very many facets angled to the façades. The problem of object complexity may lead to a compromise solution, that is a relatively simple 3-D model which can be used to index orthophotos (and even related stereomates) from which more detailed measurements can be made.

The main difference between constraints in CAD applications and constraints in photogrammetric applications comes from the difference in use of the two types of applications. CAD is used during the construction period of an object while photogrammetry is applicable to restoration. At the design stage, product features need to fulfil certain requirements, e.g. to be parallel or perpendicular or to have a specific value, whereas during reconstruction the measured dimensions will demonstrate differences from the intended values.

4.6.2 Manipulation and CAD systems

Precise 3-D coordinate measurement with close-range photogrammetry can be done in real-time, for a variety of applications [Grün, 1994], but particularly computer modelling. Computer models for visualisation require valid boundary descriptions of the object. Photogrammetry's 3-D coordinate measurement capability can supply the boundary descriptions. CAD systems can construct such a model. The creation of an interface between photogrammetry and CAD is thus required.

The function of an interface can vary from a tool for reformatting the 3-D coordinates into a CAD readable format, to a tool for adding the topology that enables the transfer of a complete object model to an Information System. The topologic information can be added using a CAD system, with the design functionality of the system also being used to construct edges and faces. This approach is suitable for polyhedral (polygonal) objects such as buildings.

An alternative to adding the topology information with the help of a CAD system is to perform this step as a part of the interface. A highly automated photogrammetric system can be regarded as an advanced interface between photogrammetry and CAD that requires object knowledge. The topology can be automatically generated. Adding more knowledge on the shape of the object at this interfacing step allows simultaneous structuring of nodes, arcs and faces. These are not merely 3-D coordinates that are transferred to the CAD system, but the shape parameters derived from them. The relationships established among the points and the faces are organised in a 3-D topological model. The 3-D topological model is a typical example of B-rep, i.e. it maintains arcs, nodes and faces to store the shape of an object. Using this model, faces are described by a sequence of oriented arcs.

The key characteristics of data manipulation are support of 3-D geometry and topology for extended spatial analysis, and facilitating interactive visualisation. The 3-D topological model supports the four geometric abstractions of spatial objects, i.e. point, line, area and body. The representation based on two constructive elements (nodes and faces) is sufficient for the derivation of a large number of 3-D topological relationships [Zhou, 1998]. Limitations imposed on faces (related to connectivity, convexity and ordering) as well as the supplementary information maintained for objects (such as materials, hues) ensure the correct rendering. The designed model is successfully linked to developed procedures for data collection. Using a digital photogrammetric system, semi automatic geometric modelling and automatic texture extraction should be achieved.

4.6.3 Mathematical Models in CAD Systems

A computer graphic visualises a mathematical description of points, lines, areas and bodies. Vector graphics are used to represent objects with smooth lines and hard edges. Since vector graphics are not made up of pixels, they can be resized, stretched or enlarged indefinitely without loss of quality. Vector graphics are created in a drawing program such as AutoCAD [Demers, 2000].

As indicated in the previous section, the geometric modelling techniques of CAD systems are available to perform the model construction according to the model convention being applied. The most common type of CAD model associated with photogrammetry is B-rep. Applying geometric object constraints within the B-rep means the recognition of points and lines that relate to the vertices and edges of the object and the automatic establishment of topologic relations between them.

CAD-based photogrammetry allows photogrammetric modelling within the interface of the CAD system and supports the advanced modelling functionality of the CAD system [Streilein, 1994]. In CAD-based photogrammetry, as Luhmann [1998] explains, the mathematical model used depends on the type of geometric modelling chosen. B-rep is the most common. Such an object description is suitable for a complex building with planar faces. The advantage of a polyhedral B-rep approach to CAD-based photogrammetry is the availability of object features (vertices and edges) in the images for measurement.

The main advantages of the parametric representation introduced in Chapter 2 are the use of image lines as observations and the way in which the model facilitates the incorporation of all types of geometric object constraints. Least squares adjustment allows an exact assessment of the precision of the computed parameters and allows for statistical testing to detect possible errors in the observations and the constraints.

4.6.4 AutoCAD Applications: Advantages and Disadvantages

AutoCAD has many advanced features - high resolution, 3-D, many different colours, patterns, etc., that can help an architect or designer present ideas to users. But most valuable amongst these, is its 3-D modelling, the layered structure of AutoCAD drawings, surface modelling, solid modelling and rendering.

The digital data captured by stereo photogrammetry can be used to create 3-D wire-frame models forming the basis for producing 3-D visualisations of cultural objects. The AutoCAD environment supporting 3-D feature extraction routines provides a first step towards the integration of photogrammetric measurement and the interpretative process of evaluating the object and making design decisions. The automatic data transfer of the photogrammetrically generated digital surface model to AutoCAD represents a second step towards the integration of photogrammetric knowledge and the interpretative process of evaluating the object by providing a flexible 3-D geometric object description suitable for the CAD (and the GIS) environment. Once in the AutoCAD environment, the user is able to perform the whole reconstruction of the 3-D objects without further manual measurements.

Layer commands and associated options provide the user with a convenient method of logically grouping graphics objects such that each group is displayed in a visually unique way. Since the layer is transparent, other layers can be seen through it (note: standard ArcView does not support layer 'transparency'). The attributes of layers can be set and viewed in the "Layer Control" dialogue box, which groups layer information into categories that are easy to read and understand. It is often useful to visualise a drawing of a 3-D object in terms of a picture of the object itself. With sufficient proficiency in 3-D design and rendering, it would be relatively easy to make changes in an interior design, for example, and then display the results.

AutoCAD has been used in many industrial, architectural, archaeological and engineering applications [Petran *et al.*, 1996]. This is because AutoCAD provides much support for modelling, including coordinate system selection, surface and solid modelling. In AutoCAD 3-D modelling begins with the selection of a coordinate system, the Local Coordinate Systems (LCS). Then, surface modelling creates 3D objects by joining surfaces together. AutoCAD's surface commands generate faceted surfaces using a mesh or wire-frame, where each cell of the mesh encloses a polygonal region of space. This means that AutoCAD generates only approximations to curved surfaces [Tangelder et al., 1999]. On most computer displays, the approximations are visually attractive and present minimal distortion. Surface modelling differs from solid modelling in that individual surfaces only are constructed, whereas solid modelling renders solid objects in perspective and with a lighting model. For example, a box can be defined, as an object comprised of six surfaces that are commonly perpendicular or a solid object that has six mutually perpendicular sides. The key difference is that surface models cannot be intersected, joined or subtracted as solid models can.

Surface modelling is well suited for drawing complex wire-frame meshes or for depicting sharp transitions. Edge surfaces are constructed by specifying the boundaries of a region in space. AutoCAD then interpolates an approximation to a surface that is bounded based on the curvature of the boundary objects.

Disadvantages of the surface rendering approach arise because of its computational complexity, as well as a memory requirement for retaining projection images. In addition, lighting may not be completely specified, leading to errors in simulating reflectivity and diffusion from textured surfaces.

Solid modelling allows the creation of graphic objects as though they were actual solid objects. Solid models are created (similarly to surface models) by joining various primitive shapes, which are solids. This join process can be reversed to implement solids subtraction, where one may use a given type of solid to create a hole of a desired shape in another solid.

4.6.5 AutoCAD and 3-D Modelling

AutoCAD runs on several popular computer platforms and can be used with direct database access and a well-defined database interface. The elements of the relational database may be combined with graphic entities. In general, multimedia data such as sound, raster images, raster maps, video clips and textual information are accessible via external viewers.

AutoCAD's 3-D objects include wire-frames, meshes, solids and 3-D polylines [Yarwood, 1993]. AutoCAD's 2-D objects (such as circles, rectangles, etc.) can be drawn on a plane that can be positioned anywhere in 3-D space. The Advanced Modelling Extension (AME) is an optional AutoCAD module. AME is a solid modelling program that allows 3-D solid models to be constructed in AutoCAD. AutoCAD AME solid models can also undergo Boolean operations and be converted to editable solids.

From the foregoing reference to functionalities, links to databases and other media, it is evident that AutoCAD is an appropriate environment to build an A/AIS.

4.6.6 CAD Applied to Cultural Modelling

AutoCAD was the earliest, well-known, successful PC based graphics package, thus it still 'sets the scene'. In the previous section we were reminded that AutoCAD can build 3-D models, using solids or faces, from 3-D coordinates. The latter is essentially the B-rep approach. Faces can be rendered.

ESRI, the developer of ArcGIS, ArcView etc. has a product ArcCAD. This has briefly been investigated. To quote the software's developer, "ArcCAD gives GIS functionality within AutoCAD" [ESRI, 2005]. It provides mapping, data management and display tools that work directly with AutoCAD software's design and drafting tools. It creates maps based on database attributes, combining these with AutoCAD's graphics design tools. It can be used to develop GIS themes using tools to capture selected entities from drawings based on layer, colour, and other AutoCAD properties. With the same tools, text and attributes can be loaded into databases and associated with map features. Tabular editing is performed in a spreadsheet-like environment while spatial data changes are made with AutoCAD editing tools. It provides a set of GIS selection and query commands. This is an interesting combination for the modelling of cultural objects, but is not part of the standard GIS configuration.

AutoCAD Example

3-D modelling with the CAD package AutoCAD is well established. However for completeness, an example from Calgary, Canada, producing a wireframe model (Figure 4.12) and then a rendered model (Figure 4.13) of a historic church [Habib, *et al.*, 2004], both of which could be rotated to effect different perspective views, is given.

FIGURE 4.12

3-D Wire-frame Modelling of a Cultural Object, using AutoCAD

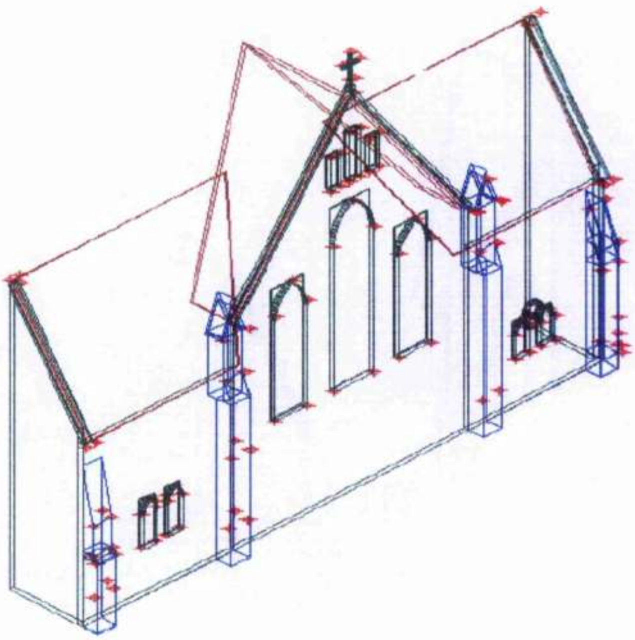
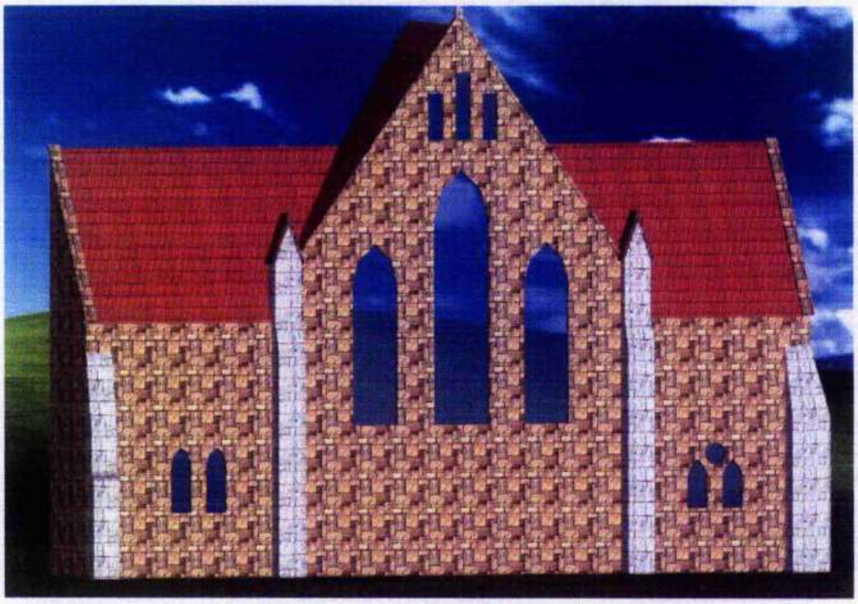


Figure 4.13

Standard Pattern Rendering of the 3-D Model of the Cultural Object Shown in Fig. 4.12, using AutoCAD



4.7 Digital Photogrammetry, CAD and GIS Integration

Standard CAD packages now support excellent 3-D representation, GIS packages less so; both require 3-D coordinates of the represented object to do so. Traditional and modern photogrammetry support the capture of 3-D coordinates. For modern photogrammetry (i.e. digital photogrammetry) these coordinates can be captured directly in digital form. The potential interdependence of CAD and digital photogrammetry is thus obvious.

Popular GIS packages such as ArcView play a less obvious role. The standard 3-D modelling tools (see Section 4.3.3) are unsophisticated. But a GIS can be considered to be a spatial information organiser, and this role is important. Such packages are user friendly and have a comprehensive and ever expanding suite of functionalities. This expansion is gained through the new options made available by the developer (i.e. ESRI in the case of ArcView or ArcGIS), tools produced by (or for) the user in a package's ADE (applications' development environment, which is AVENUE in the case of ArcView and VBA in the case of ArcGIS, for example) and direct links to other projects and other software, for example SOCET Set, AutoCAD or Excel. A GIS package can thus represent the 'hub' of a system using linked software tools and also be the substructure of such a system.

AutoDesk introduced AutoCAD in December 1982 and it has long been a leader in the CAD field. Its functionality is emulated by other packages, for example CAD tools in well-established GIS packages such as ArcView are judged by their closeness to AutoCAD's functionality.

AutoCAD was very widely adopted throughout the world for its two-dimensional capabilities, but it now has well developed three-dimensional capabilities. AutoCAD as a package right "off-the-shelf" is programmed as a general-purpose drafting and design package, but has a wide range of functionalities. AutoCAD is a principal component of Mechanical Desktop (solid modelling software) and interfaces well with 3-D Studio (rendering and animation software), both of which are produced by AutoDesk (AutoCAD's developer.) AutoCAD drawing files can be easily imported into many other software packages and GIS, and its interchange format .DXF is also a standard for the exchange of geospatial data.

As already discussed, there are essentially two models commonly used in spatial processing today. These are the *Entity* or vector model and the *Continuous Surface* or raster model. The models are not mutually exclusive as, for example, many modern GISs are able to manipulate and analyse spatial data in either form, if care is taken and the potential for error is considered, but the vector data model is supported by 3-D geometry and topology for extended spatial analysis and interactive visualisation. The model carries the geometric abstractions of spatial objects; points, lines, areas and bodies. The representation based on two constructive elements (nodes and faces or points and facets) is sufficient for the generation of a large number of 3-D models. The restrictions imposed on faces (e.g. convexity) and the additional information which can be archived for an object ensures the correct rendering and enable the design of realistic (e.g. orthophoto textured) 3-D objects.

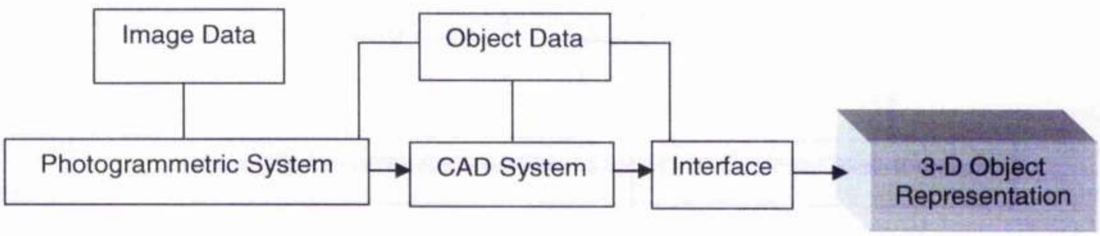
There are variations in vector functionality. In addition to the geometric abstractions, some systems allow for the support of higher-level features, for example a cluster of points or network of lines or a region of polygons. High-end spatial applications typically specify a topological data model. The topological data model is an efficient way to store information about the connectedness of features. Using this information it is relatively easy to determine which polygons are another's neighbours.

Photogrammetric systems that allow the specification of topology may be called CAD-based or GIS-based. However, in many systems topology is completely separated from geometry. Systems of this type support a photogrammetric approach to the establishment of the 3-D coordinates of object points through the measurement of points in several images. Then the points or edges that border an object facet are selected in the images, thereby building the topology of a polyhedral B-rep. As long as only triangular facets are used in this process, the topology has no geometric implications, as all facets are planar. Several commercial PC-based photogrammetric systems on the market belong to this category. But PhotoModeler allows fitting of points to a plane in post-processing. The combination of point measurement and the restriction to models based on plane triangular faces means that the use of a mathematical model based on the collinearity equations is satisfactory.

Although CAD systems evolved from 2-D tools used in applications, including design, manufacturing, quality control and facility management [Schürle, 1999], the basic functions of a *modern* CAD system are the storage and retrieval of 3-D data, and their manipulation and visualisation. These functions are also useful in a digital photogrammetric measurement system. Therefore, photogrammetry can benefit from integration with CAD. There are two main interpretations of the term CAD-based photogrammetry: algorithm based or system based. The first manifests itself as developments within the photogrammetric systems. The second manifests itself in the integration of photogrammetric tools within existing CAD systems [Maas and Vosselman, 1999]. Considering the second, the resulting 3-D object description is passed automatically to a CAD system for visualization and further architectural processing. Therefore, a digital surface model is generated automatically as all those surface features, which are defined by more than three object points, are divided into suitable triangles. The results of the photogrammetric processing are passed to the CAD system. As a result, the CAD environment is suitable for the documentation and visualization of cultural buildings (as well as other simulations, manipulations and analyses of the object).

FIGURE 4.14

The Integration of Photogrammetry in a CAD System



It is concluded that the integration of photogrammetry and CAD has great potential for expanding the acceptance of photogrammetry amongst architects and also archaeologists.

4.8 Summary and Conclusions

As yet, the Islamic Republic of Iran, for example, has not finalised a national archive of photography suitable for the reconstruction of whatever cultural objects become damaged. However, following the investigations reported in the chapter it seems that useful tools already can be found which could further enable this.

This chapter has shown that digital photogrammetry can supply the X, Y, Z coordinates of the vertices forming the polygons bounding facets. These can be exported to a GIS or CAD system. In a Digital Photogrammetric system, the generation of 2.5-D models is possible using a digital surface model and an orthoimage. This new image is a *draped* orthoimage, and can be used to render a B-rep model, on a facet-by-facet basis. Digital photogrammetry can also supply textural information from surface models of façades that can, potentially, be used in the rendering of 3-D models produced from photogrammetrically derived X, Y, Z points.

It has been shown that the 2.5-D model suitable for representing the topographic surface, in the GIS examined (ArcView), by draping a single orthophoto (or orthophoto mosaic) over a surface model cannot be used, on its own, to represent a multi-faceted 3-D object, as it assumes that any X, Y coordinated point has a unique Z value. This cannot be the case with a building – at the simplest level both a roof point and a floor point can have the same X,Y coordinates but will have different Z coordinates. Instead, facet by facet, the model has to be constructed using photogrammetrically derived X,Y,Z coordinates in a single local coordinates system. The resulting 3-D model can be used as a 3-D model of the object (see Figures, 4.6, 4.7 and 4.8) or as an index to appropriate hotlinked photos, orthophotos and surface models ('hotpics' in Figure 4.2, 4.3) and documents ('hotdocs' in Figure 4.3 or documents as shown in Figure 4.1) and for further measurement and analysis, as required. In this way an off-the-shelf GIS could become the corporate DBMS, the hub, for a national archive of photographs of cultural objects.

Given the powerful 3-D modelling and rendering capability of a CAD package such as AutoCAD and the fact that for many engineers and architects this package, rather than a GIS package, is likely to represent the preferred hub of an A/AIS, then another solution might be that offered by ArcCAD, which gives some GIS functionality to AutoCAD. However also relevant is the 'linking' capability of AutoCAD, which will allow the analysis, manipulation or augmentation of a CAD model by linked packages such as SOCET.

5. An Investigation of Architectural and Archaeological Tasks Involving Terrestrial Photogrammetry

5.1 Introduction

In this chapter there follows an investigation of seven survey projects in the archaeological and architectural (or cultural) domain, that were addressed in recent years. This builds on the review of the Windsor Castle photogrammetry and simulated station building GIS cases presented in the preceding chapter.

In the first two cases, of the seven addressed in this chapter, the technological solution involved the use of hardcopy photogrammetry and CAD, as well as terrestrial photography, in projects carried out by organisations external to Glasgow University. Although the technological outcomes of the investigations in which the author has been directly involved and reported on in this thesis do not involve hardcopy photogrammetry, it is worth identifying what the aims and outcomes of these two cases were. This is in order to ensure, for example, that a system based on digital photogrammetry data capture in a Geographic Information System environment adequately meets the requirements of the 'cultural' domain, at least with respect to projects successfully completed. Hence these two cases:

1. The Photogrammetric Survey of the Amphitheatre at Side; and,
2. The Photogrammetric Survey of the Tomb of Christ

are briefly summarised, in the next section.

The remaining five cases relate to tasks being addressed by colleagues from Glasgow University, or elsewhere, which the author investigated. In some cases the author's involvement was minimal affording him an opportunity to work with professionals who were required to record a building, and allowing him an opportunity to gain some preliminary experiences; for example, this was the situation for the Strome Castle case. The cases in which the author was directly involved and which are considered in later sections of this chapter are:

1. Strome Castle in Scotland, in which the author was an observer;
2. St. Avit Senieur Abbey in France, in which the author was an investigator;
3. Gilbert Scott Building of Glasgow University, in which the author was an investigator;
4. Anobanini Project in Iran, in which the author was an investigator; and
5. Hunter Monument Glasgow University, in which the author was an investigator.

Through projects of the type described in this chapter, and the Windsor Castle case in the preceding chapter, common traits emerge. The Zeiss UMK 10/1318 is an effective popular camera and it can be seen that a facet based method has become common. This aligns with the B-rep approach advocated in section 5.3.3, where each facet is treated separately. Accuracies of under 10mm can be expected.

5.1.1 Example Hardcopy Photogrammetric Surveys

From the two cases described in this section surveying on the basis of facets, using targeted and untargeted control points and an eventual accuracy (RMSE) for derived points of about half a centimetre seems to characterise such projects.

The Photogrammetric Survey of the Amphitheatre at Side

The Amphitheatre of Side, Turkey, was constructed about 100-150 AD [Özdura,1975], with a diameter of 119.60m and a seating capacity of about 17,000. It consists of 51 seating galleries and connecting radiating staircases. 23 arches support the stage. The Architectural Photogrammetry Centre of The Middle East Technical University of Turkey was contracted to carry out the photogrammetric survey, in 1971, for restoration purposes.

The photogrammetric survey assisted in a program for the amphitheatre's restoration. The scale of this project's map product was 1/50; required 436 control points, observed from 75 stations; and used an SMK 120 camera and Zeiss Terragraph plotter. The seating galleries supported the camera tripods.

To obtain good stereo-coverage, pictures were taken at every fifth row of seats, providing a height-difference of two meters. There were five consecutive stereo-pairs in the vertical direction. In the upper roof where the diameter was largest, it became impossible to observe detail closer than 15m from the camera station. In all, 144 stereo-photographs were taken. Stereo-photography of the arches were taken separately. The facets of each arch were plotted separately as a single drawing. Accuracies (RMSEx, RMSEy, RMSEz) achieved were 5mm – 8mm.

The Photogrammetric Survey at the Tomb of Christ

The Department of Civil Engineering at City University, London completed this survey of the Tomb of Christ in Jerusalem in 1993. The investigation carried out by Robson et al. [1994] exploited different photogrammetric techniques to support the restoration of this monument. Details can be found in Cooper et al. [1992].

Photo control included: survey measurement such as slope distances, horizontal and vertical angles; 3-D coordinates of surveyed points; and a framework of surveyed measurements and points for camera stations, natural features (untargetted points) and targetted points.

Images were taken with a Zeiss UMK 10/1318 camera using glass plates coated with Agfa Avipan 100PE emulsion. The UMK camera was too large for inside the tomb, so a Hasselblad SWC camera with a 100-point plate and fixed focus (1.2 m. to ∞) and Ilford FP4 film were also used. Photographic processing was performed in the bathroom at a guesthouse. Sketched features for untargetted control points were produced. Unfortunately, there were many photographs containing no recording of surveyed points. At least four fiducial marks were needed in an image.

The outcome included photocoordinates of 400 targetted and untagetted points; tests revealed these had an accuracy (RMSEx, RMSEy, RMSEz) of 3.5 and 4.6mm respectively. An Oracle relational database was created to manage the scanned colour photographs of each stone and related textual information. A method was achieved to delineate stone boundaries manually or semi-automatically which were then used as 3-D breaklines for an automated DTM procedure. A primitive boundary for a CAD model of each piece of stone was plotted using conventional photogrammetry. In this example, the detailed 3-D model of the tomb was constructed within Intergraph MicroStation CAD software and a computer graphics copy of the tomb was created. Texture maps have been generated from images acquired on site. An appropriate surface model has been fitted to the data. Each structural element has been modelled in 3-D using the existing geometric CAD system.

5.2 The Photogrammetric Survey of Strome Castle in Scotland

Strome Castle is a ruined castle located in North West Scotland in the Loch Carron, Ross and Cromarty area, which has historical associations with the Lords of the Isles. The abandonment of Strome Castle was reported in 1602 AD and its decay has advanced steadily since then.

5.2.1 Description

The survey of Strome Castle is a project of Glasgow University Archaeological Remediation Division (GUARD). The author accompanied GUARD on an excavation to the castle to gather photography and photo control to investigate the 3-D modelling of the castle, for future renovation, if required. It was thought that archaeologists could, in a user-friendly environment capture 3-D coordinates, for future renovation, and could use digital photographic data. These data could also be used to create 3-D models for the visualisation of the castle.

5.2.2 Data Capture

To capture data a DC260 Kodak digital camera was used. This photography covered the existing walls of Strome Castle. There were 80 photographs taken from the variable distances to the walls, but not greater than 15 meters. The scale of the photography was always about 1:500. Before photography, adhesive "butterfly" targets were attached in appropriate places. Between 4 and 6 targets can be found on a photograph. The overlap of the photographs is about 65%. Figure 5.1 shows 2 photos with about 70% overlap and their targeted points.

FIGURE 5.1

Two Overlapping Photographs of the North Wall of Strome Castle, with some targeted points. The original photoscale is about 1:500

5.2.3 Importing Data

The digital photographs were examined to select the good photographs which also ensured the coverage of all sides of the object. The selected data were processed in the PhotoModeler program (PMP) to provide a selected set of coordinated surface points. Table 5.3 lists 63 of these from the orthophoto shown in Figure 5.2.

5.2.4 Processing

Processing the Strome Castle photographs was done with PMP software. This is a low cost interactive photogrammetric package also considered in the Hunter Memorial and Anobanini projects. Using the PMP approach to obtain coordinated points, there are eight steps in creating a 3-D model:

1. Create a camera calibration report,
2. Plan the measurement of the object,
3. Capture photographs of the object,
4. Import the captured photographs,
5. Select (or "mark") the features on one photograph; these will be 3-D vertices (either control points or feature points),
6. Identify the same 3-D vertices on the other photograph,

7. Process data, and
8. Export the results in the form of 3-D coordinate data for vertices – for example to AutoCAD.

PMP also produces orthophotos (see Figure 5.2). In TIFF format these can be exported to packages such as ArcGIS, for further coordinate capture. Figure 5.2, as well as being the orthophoto has superimposed on it the results of digitizing one stone block on the orthophoto. This blocks coordinates are points 18-64 in Table 5.1 and are features not originally 'marked' and captured during the processing described above.

FIGURE 5.2

An Orthophoto Image of Strome Castle (a Part of North Wall), showing one block (points 18-64 in TABLE 5.1). Two targeted points show.

TABLE 5.1

3-D Points in the wall of Strome Castle derived using the PhotoModeler Program (Points 1-17 are targeted, points 18-64 are the outline of a block)

ID Points	Photos	X (m)	Y (m)	Z (m)
1	1,2	0.392289	0.119215	-1.430730
2	1,2	0.039813	-0.004836	-1.408228
3	1,2	0.581791	-0.175403	-1.287289
4	1,2	0.568741	0.390494	-1.542090
7	1,2	-0.166837	0.411033	-1.609436
8	1,2	0.174026	0.219887	-1.501594
9	1,2	-0.113162	0.056933	-1.448310
10	1,2	0.069247	-0.128822	-1.348557
11	1,2	0.194784	0.409425	-1.582918
13	1,2	0.607403	0.460127	-1.564232
14	1,2	-0.024101	0.173801	-1.497178
15	1,2	0.109081	0.085032	-1.441548
16	1,2	0.449351	-0.137557	-1.316848
17	1,2	0.200171	-0.040302	-1.379903
18	1,2	0.530297	0.325612	-1.518312
19	1,2	0.538248	0.326053	-1.519147
20	1,2	0.539626	0.330192	-1.520543
21	1,2	0.547873	0.329592	-1.526039
22	1,2	0.552440	0.324939	-1.521025
23	1,2	0.559004	0.319865	-1.520374
24	1,2	0.566149	0.314705	-1.521439
25	1,2	0.576430	0.313365	-1.523535
26	1,2	0.583466	0.309461	-1.523039
27	1,2	0.589752	0.301221	-1.509690
28	1,2	0.594672	0.294517	-1.506133
29	1,2	0.604993	0.287472	-1.500478
30	1,2	0.612526	0.279148	-1.493672
31	1,2	0.619628	0.273258	-1.491490
32	1,2	0.625743	0.269667	-1.492305
33	1,2	0.624007	0.264894	-1.499167
34	1,2	0.612606	0.261262	-1.486113
35	1,2	0.603026	0.262564	-1.488766
36	1,2	0.597117	0.256934	-1.489564
37	1,2	0.590445	0.257291	-1.491776
38	1,2	0.575182	0.257478	-1.484151
39	1,2	0.561736	0.254974	-1.476230
40	1,2	0.547136	0.252539	-1.467331
41	1,2	0.541186	0.252743	-1.480338
42	1,2	0.530596	0.253564	-1.481576
43	1,2	0.521658	0.254765	-1.482458
44	1,2	0.513450	0.250883	-1.479069
45	1,2	0.503264	0.250619	-1.478997
46	1,2	0.495645	0.254010	-1.482532
47	1,2	0.487599	0.258354	-1.487704
48	1,2	0.479399	0.259900	-1.482770
49	1,2	0.476461	0.263582	-1.487607
50	1,2	0.472640	0.267740	-1.492555
51	1,2	0.468327	0.270002	-1.492970
52	1,2	0.463570	0.272841	-1.490431
53	1,2	0.459728	0.274981	-1.506160
54	1,2	0.460094	0.282445	-1.504305
55	1,2	0.464813	0.286727	-1.502079
56	1,2	0.471740	0.288953	-1.504282
57	1,2	0.477691	0.291257	-1.498744
58	1,2	0.484941	0.293415	-1.494799
59	1,2	0.492714	0.296273	-1.496811
60	1,2	0.500037	0.298848	-1.497355
61	1,2	0.504265	0.302226	-1.495274
62	1,2	0.511135	0.309250	-1.506823
63	1,2	0.519724	0.313890	-1.515149
64	1,2	0.525772	0.322018	-1.523830

5.2.5 Extracting Data

Linking techniques are supported by ArcGIS to allow access from the so-called view object (in ArcGIS a typical view object is the active view currently being displayed in the working window) of one project, which may be a simply rendered building face defined by a polygon whose coordinates have been exported from PMP to a view object in another project (such as Figure 5.4). This facility can be used to access more complex information such as documents, texts, diagrams, digital photos and DXF data files. Or this can be done to obtain more measurements in A/AIS applications, where, for example, renovation is needed.

As mentioned, in Table 5.1, 3-D points from 18 to 64 are the vertices of a stone which is a part of Strome Castle's Wall. These coordinates could then be accessed by a script file (3dpoly.scr file applicable in the AutoCAD environment), which uses these 3-D points to draw a wire-frame of the object. A 3-D surface model from AutoCAD could then be rendered and enhanced. Such a model is more informative to renovators than the orthophoto archived within the GIS.

5.2.6 Product Accuracy and Outcomes

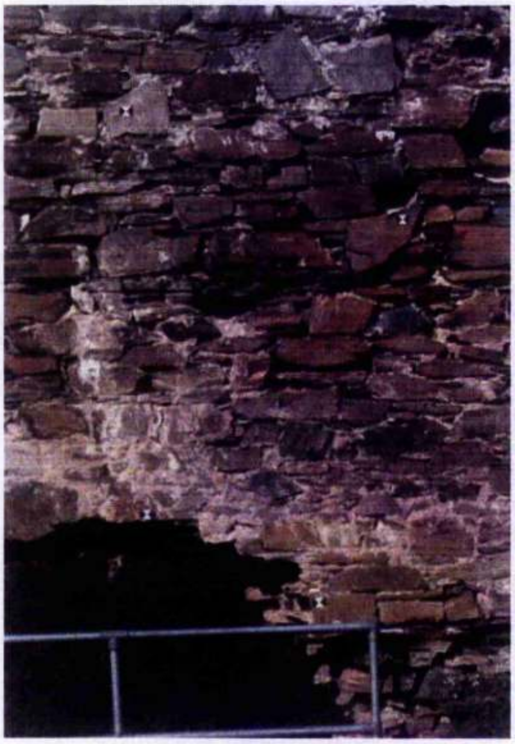
A theoretical product accuracy can be calculated based on the repeatability of measurements to a point. To quote the classic computer graphics text of Newman and Sproul [1973] (ref Principles of Interactive Computer Graphics, 1979. McGraw Hill, New York) repeatability is the maximum distance between any two repeat measurements. Newman and Sproul link this to what is nowadays referred to as accuracy (a measure of the distance from the ideal location to the actual location), and following work reported by them this is typically 3.5 pixels in the X or Y directions – or 5 (4.9) pixels in plan. 5 pixels in the orthophoto shown in Figure 5.3 is 10.52mm (based on a camera focal length of 28.38mm, CCD diagonal of 1524 pixels and 9.11mm)

A second orthophoto (Figure 5.3) was produced from which some accuracy figures were derived. This records a barrier fence. Distance measurements to points along this fence, taken in the field and subsequently compared to measurements on the orthophoto revealed an accuracy (RMSE) of about 10mm. (The measurements used in this determination are not now available.) It can be noted that the actual accuracy (about 10mm) and the theoretical accuracy (10.52mm) of the orthophoto are similar.

This investigation has shown that PMP can export 3-D coordinates of points which can be used by AutoCAD and ArcGIS, and orthophotos which can also be exported to the ESRI GIS environments where graphic editing tools can support stone by stone representation and capture as well as other GIS functionality.

Figure 5.3

An Orthophoto Image of Strome Castle (a Part of South Wall), showing the barrier fence used in the accuracy check



5.3 The Photogrammetric Survey of St. Avit Senieur Abbey in France

In this project, metric terrestrial photography was gathered to provide an archive of an abbey of St. Avit Senieur as it was undergoing restoration. Photography was taken only of those parts after they were restored. Much was still undergoing restoration, and covered in scaffolding (see Figures 5.5, 5.7). It was hypothesised by Ian Pickering, an architecture lecturer in the Glasgow School of Art (Postgraduate Department of Architecture), that very subtle changes in wall curvature would be detected and assist identification of the construction eras for the abbey. It was the testing of this hypothesis that had attracted some AHRB funding. The funding including a two week stay at St Avit by the author and a one week stay by the author's supervisor and the departmental photographic technician. The photographic technician set up a photographic lab in the guest house bathroom for developing film and guided the author in his photographic tasks. The St. Avit Abbey project allowed an investigation of how digital terrestrial photogrammetry can assist in the gathering of the 3-D coordinates of a cultural object, and also how the collected data could be input to GIS.

Unfortunately the smooth freshly renovated and limed light coloured walls of the Abbey (see Figures 5.4 and 5.5) did not allow for good image matching, and the resulting photogrammetric solution was of inadequate quality to reveal the subtle changes in wall curvature. This was a great disappointment to colleagues in the Post graduate School of Architecture at Glasgow School of Art. However procedures used to gather the data are recorded here for future reference.

The Saint Avit Senieur Abbey was built in the years preceding 1117. Its approximate dimensions are 53 x 21 x 32 meters. It was probably constructed with three domes, with two fortress towers added in the 12^{th} century. St. Avit is located in a village formerly called "*Castrum Sancti Avit Senioris*". The village is about 120 Km to the west of Bordeaux in France. St. Avit is situated on a headland facing south and has been occupied by man, uninterrupted, since prehistoric times. In the Iron Age, the place already fulfilled a sacred function because a pagan temple was later discovered where, it was said, 3000 idols were worshipped.

Figure 5.4 shows the UMK10/1318 film based camera located inside St. Avit Abbey in France used to capture of photographs and Figure 5.5 shows an inside-view of the Abbey, with some of the scaffolding used by restorers. Both figures show the light coloured walls.

FIGURE 5.4

The UMK10/1318 Camera Located Inside St. Avit Abbey for Photography

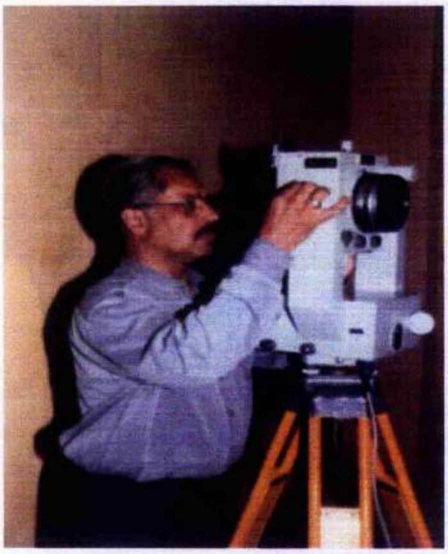
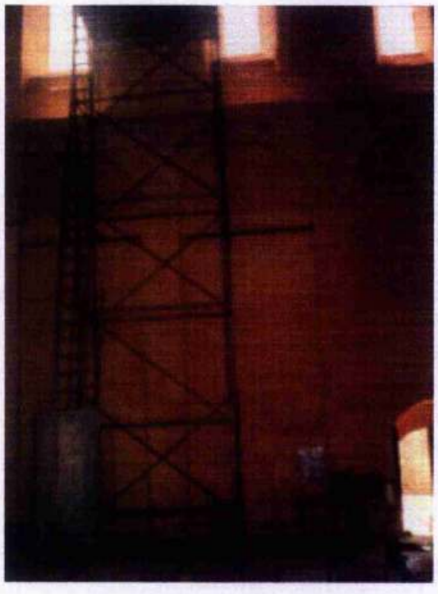


FIGURE 5.5

An Inside View of Saint Avit Senieur Abbey in France



5.3.1 Photo Control

Photo control was obtained using a 1" theodolite and tape. Photogrammetric measurement used SOCET SET. As would be expected, a lot of experience was gained from the survey - useful in applying terrestrial photogrammetric techniques in the future.

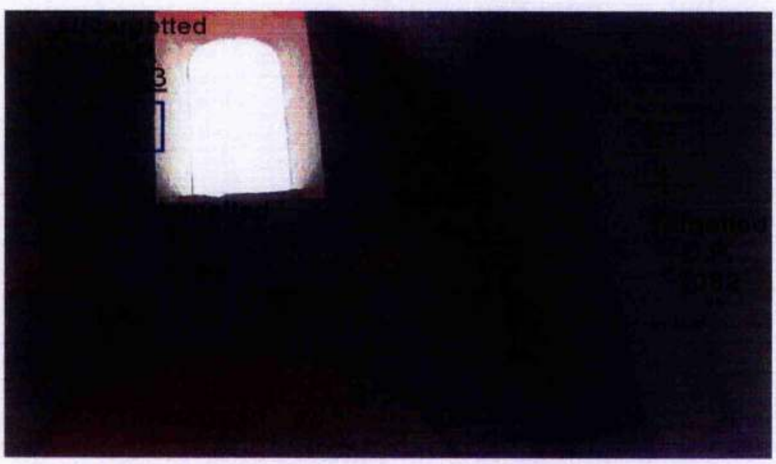
To provide photo control, a permanent marker was established on the top of a small metal bolt placed in concrete, in the street below the abbey and to its south-west, with two references for orientation. From this origin a traverse of stations within the abbey was all coordinated, by ground survey methods, from which control points for the photogrammetry could be established.

Some eighty-control points were obtained, overall. The approximate locations of two untargetted control points and a targetted control point located on a part of the south wall (inside) are given in Figure 5.6.

FIGURE 5.6

The Location of Control Points on the Wall (Inside Abbey)

(Index Photograph P0000503.tif)

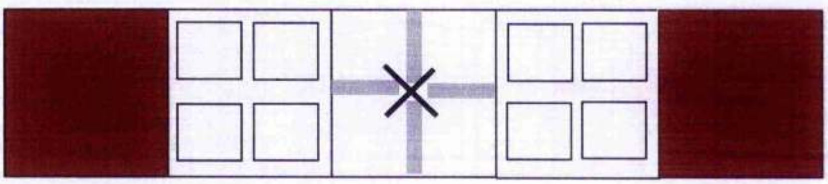


In photograph P0000503.tif (Figure 5.6), taken with a Kodak DCS 420 camera, the locations of two untargetted control points (2022 and 2023) and a targetted control point (1032) are indicated. This is one out of a number of similar digital photos collected to provide a description of the control points. The inserted location detail is with respect to the targetted or untargetted control points. For example, the location of untargetted control point number 2022 is marked with a blue rectangle and annotated with its number in Figure 5.6.

Figure 5.7 shows the graphic description of untargetted control point 2022. The precise location (black X) of this control point is at the '***centre of paler cross forming centre of White Square of the frieze sequence***' (this is the recorded textual description).

FIGURE 5.7

Graphic Description (Digital Sketch) of Untargetted Control Point 2022



Tables 5.2 and 5.3 give the precise location and coordinates of control points with respect to the interior wall.

5.3.2 Imagery

The acquisition of photography was the first consideration in this task. To cover the entire St. Avit abbey building with photos, there was a plan for taking stereo photography using a metric terrestrial camera of all four aspects, inside and outside of the abbey, and the ceiling. This archive would be useful to complete a reconstruction model of the building. However, the plan could not be achieved in the summer of 2000 because most of the area was covered with scaffolding and construction workers. Therefore, a part of St. Avit building was chosen. The arrangement was set up to be suitable for investigating applying a digital stereo photogrammetric approach to modelling the abbey.

The image acquisition with both cameras (UMK 10/1318 Zeiss and DCS 420 Kodak Professional Digital Camera) took place almost simultaneously. The main purpose was to capture any detail of the object from at least two perspectives to allow the restitution of the object from stereo image pairs. The DCS 420 was used to produce image sets of JPEG format file (but it is possible to convert to an uncompressed TIFF format – suitable for inclusion hotlinked to ArcGIS) of the untargetted control points, which were digitally annotated; verbal descriptions of these control points were also prepared, see Table 5.2 for further details of some control points using this approach. The product of UMK 10/1318 (film negatives) had to be digitised (scanned) before more processing. This was done using a Vexcel scanner of the company SDS.

Wherever possible photography was taken at about 1/50 scale (as recommended in sections 1.2 and 5.2.3) but on many occasions larger scales had to be adopted because of difficulties in getting far enough away from the structure. For photography with UMK 10/1318 Zeiss camera, of that part of the abbey not covered in scaffolding, twelve camera positions were required to give complete coverage and sufficient overlap between the stereopairs. These were positioned in two rows of six shots forming a block of photography. At each station, the camera was set at its lowest position on the tripod, approximately 1.4 meters from the floor level. Fortunately, almost all photography was acceptable; a few extra exposures were needed. The total photographic operation was completed in approximately ten hours including the test exposures, setting up the control, establishing the darkroom, photographic processing and finally disassembling all the equipment. The photography was taken from 7^{th} to 12^{th} July 2000.

It was assumed that a photogrammetric survey would be a most reliable support for future renovation, thus the following archive would be appropriate:

60 photos of interior building façades taken with a UMK 10/1318 Zeiss Jena camera;
37 annotated photos of control points taken with a DCS 420 Kodak Digital Camera;
17 textual descriptions of untargetted control points;
17 graphic descriptions of untargetted control points; and,
3-D coordinates of all control points in a local coordinate system.

On return to Glasgow the photogrammetric solution was investigated, with the expectation that, unless considered unsuccessful, the remaining internal and external walls would be photographed in a later season once the scaffolding (see Fig. 5.8) was removed. Because of difficulties with image matching the photogrammetric solution was unsuccessful and the site was not revisited.

FIGURE 5.8

An Outside View of Saint Avit Senieur Abbey in France

TABLE 5.2

Location of Untargetted Points in Named Index Photographs

Facade	Point No.	Textual Description of Control Point
North-wall (Inside)	2001	Point is at the centre of intersecting (red) 'x' lines (P0000474.tif)
	2002	Point is at the centre of intersecting (red) 'x' lines (P0000474.tif)
	2002A	Point is indicated in the corner of black-on-white right-angled pattern below cornice (see P0000476.tif)
	2004	Point is at point where upper cross bar of the window meets the edge of the bar running around the window arch (P0000477.tif)
	2006	Point is at apex of the window arch, at the contact point of the topmost detail which is half an 'x' shape (see P0000479.tif)
	2007	Point is where upper cross bar of left window meets strut running down edge of window (see P0000480.tif)
	2009	Point is at corner of intersecting (red) 'x' lines above the doorway in the west wall of the bay above the cornice (see P0000484.tif)
South-wall (Inside)	2015	Point is at intersection of window struts – 3rd intersection up and 1st intersection in (see P0000491.tif)
	2016	Point is at lower corner of upper edge of cornice (P0000492.tif)
	2017	Point is at the centre of intersecting (red) 'x' lines (P0000494.tif)
	2019	Point is at centre of paler cross-forming centre of red square of frieze (see P0000497.tif)
	2019A	Point is at point where window's upper cross strut meets the window's left vertical strut (see P0000497.tif)
	2020	Point is at top of North East most vertical scaffold support
	2021	Point is at top of North West most vertical scaffold support
	2022	Point is at the centre of paler cross forming centre of white square of the frieze sequence (see P0000503.tif)
	2024	Point is at the centre of intersecting (red) 'x' lines on the arch (see P0000504.tif)
	2026	Point is at the centre of intersecting (red) 'x' lines (P0000506.tif)

The Table 5.3 coordinates relate to the untargetted and targetted control points located on a part of the Inside-North-wall of St. Avit Senieur. These control points appear on a stereopair of photographs, but the targetted control points were removed after the field season of summer 2000, for reasons of conservation.

TABLE 5.3

Shows the Coordinates of Photo Control Points

Point	X (m)	Y (m)	Z (m)	Description
1004	148.930	130.864	103.174	Targetted point
1005	146.917	135.684	107.729	Targetted point
1006	153.800	132.926	103.139	Targetted point
1007	151.760	137.609	107.525	Targetted point
1008	158.822	136.175	104.009	Targetted point
1009	156.878	139.918	107.137	Targetted point
2002A	147.856	142.073	112.460	Untargetted point
2003	147.054	145.682	117.142	Untargetted point
2004	149.673	145.086	115.988	Untargetted point
2005	149.229	142.017	112.387	Untargetted point
2006	152.147	147.865	120.318	Untargetted point
2007	154.502	144.252	115.427	Untargetted point
2008	156.557	140.608	111.425	Untargetted point
2009	156.845	143.365	113.224	Untargetted point

5.3.2 Fiducial Marks

The UMK 10/1318 is a metric camera with a picture size of 120 mm x 166 mm. There are four fiducial marks located for photogrammetric purpose, middle bottom, middle top, middle left and middle right. The focal length of camera is 99 mm with a focus setting from ∞ to 1.4 m.

5.3.3 Digital Data

The data set of St. Avit Senieur Abbey has been gathered as part of an investigation to provide a basis to test and compare different digital techniques, software facilities and instruments in order to obtain geometric, thematic information of a building, and methods for recording, retrieving and maintaining this data set. The data set is applicable to all digital photogrammetric techniques for the reconstruction of cultural objects, including 3-D building restitution, stereo photogrammetry, single image rectification, image mosaicing and CAD coverage.

5.3.4 Data Processing

Four photographs were chosen for digitising and used together with the other data (digital imagery of control points, control points coordinates, textual description, etc.) in the Digital Photogrammetric Workstation with SOCET SET software for further processing. As indicated at the beginning of section 5.3 the outcome of the photogrammetric restitution was unsatisfactory, because of the nature of the photographed walls. This was a great disappointment to the author and also to colleagues from the Architecture Department at Glasgow School of Art whose AHRB project had funded the author's visit to St Avit. Consequently publishing the results was discouraged. The author understood this to include his thesis.

5.4 The Survey of the Gilbert Scott Building at Glasgow University

The Gilbert Scott Building is, to the public, the main and now second oldest property of the University of Glasgow. The oldest building is the gatehouse known as Pearce Lodge, which was reputedly transported from the university's original sixteenth century location in Glasgow High Street.

5.4.1 Description

A part of the south view of the Gilbert Scott Building was chosen for a 3-D data capture investigation using photogrammetry. The UMK 10/1318 Zeiss Jena Camera was used for photography and a 1" theodolite was applied to obtain the control points.

5.4.2 Photo Control

The photographs were taken by the UMK from two different ground stations. For the base of the survey, two stations were selected. The stations were fixed on the ground, about 20 meters from the building. The two best photographs were digitised and made ready for using in the Digital Photogrammetry Workstation (DPW) with SOCET SET software. There were 6 targetted control points and 10 untargetted control points per stereo-pair. Figures 5.9 and 5.10 show example targetted and untargetted points. Also,

APPENDIX D shows the coordinates of selected targetted and untargetted points, used for further processing in the DPW employing SOCET SET.

5.4.3 Imagery

All photos were taken from the two-fixed station on the ground. In this survey, 10 photographs were taken used the UMK10/1318 film based camera. The scale of photography was approximately 1:60. Two photos were selected for digitising and further processing. Figure 5.9 shows one of 2 digitised photos and Figure 5.10 demonstrates an illustration of targetted and untargetted points on the Gilbert Scott Building.

The results were used for DTM generation, automated reconstruction, feature extraction and object modelling represented in AutoCAD.

5.4.4 Fiducial Marks

Four fiducial marks were used for the orientation of the photographs.

5.4.5 Product Accuracy

The accuracy of measurement and derived data were achieved from Least Square Estimation and a bundle adjustment carried out as Cooper *et al.* [1992] noted. The estimated standard deviation of the coordinates of 14 control points after the adjustment was between 2 mm and 7 mm.

FIGURE 5.9

South View of the Gilbert Scott Building

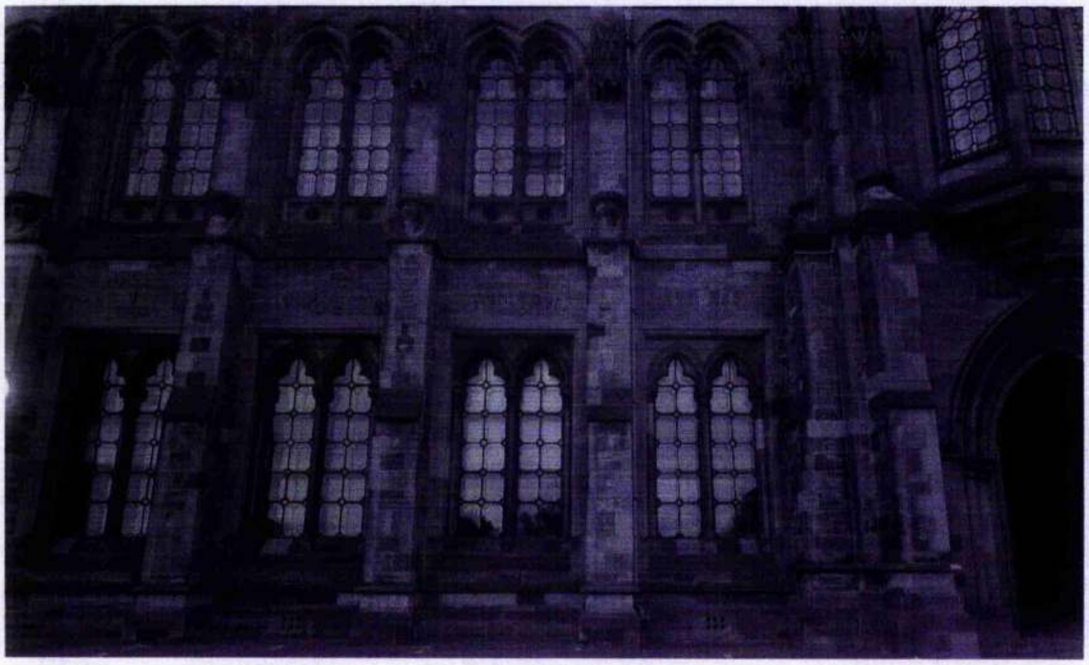


FIGURE 5.10

Shows a Sample of Targetted and Untargetted Points Selected on Fig. 5.9

5.4.6 CAD Layers

The CAD software of Intergarph Microstation (Bentley) was used in this investigation, where the detailed 3-D surface model of a part of the Gilbert Scott Building was constructed within Intergraph Microstation's CAD software, using 3-D coordinates derived from digital photogrammetry (Socet Set). The following tasks have been completed, in a limited area:

- A computer graphics 3-D representation of a window bay has been created.
- Texture from images acquired on the site has been acquired.
- Ray traced and rendered images have been created.
- The information has been managed in a GIS environment.
- The derived data points have been checked within the 3-D visualisation environment provided by AutoCAD and PMP.
- A textured surface model of a window bay has been fitted to the data.

5.5 The Photogrammetric Survey of the Anobanini Project in Iran

Prior to the author's involvement in this investigation five convergent photos (using approximately 1:50 scale photography including visible damage, e.g. cracks) of the Anobanini Rock Sculpture were captured, using a SONY DSC-F828 digital camera, by IPCO (Iranian/Persian Professional and Cultural Organisation). This represents a stage in archiving the country's cultural heritage. The author investigated the use of this photography for the 3-D modelling of part of the sculpture – a necessary step should any maintenance be required.

5.5.1 Description

The investigation of an Archaeology/Architectural Information System (A/AIS) has been carried out recently using the Anobanini Rock Sculpture at Sar -e Pole Zahab in north-west IR Iran [http://www.anobanini.ir/index/en/travel/anobanini.htm]. An objective of this investigation was to use the archived photography to describe the sculpture at Anobanini Rock using a 3-D surface model.

The comprehensive documentation of a cultural object requires that reconstructing the whole object both geometrically and pictorially is achievable. Digital photogrammetry techniques and digital facet modelling (involving representation of the object by surfaces instead of lines) combine the integration of the geometric and the pictorial characteristics of a building. Additional information is accessible through the "hotlinking" or an equivalent facility. The elements of the relational database can be integrated with graphical entities like raster images and textual information for visualisation. The output of digitised points can be fed directly into a 'hub' package such as AutoCAD.

In this project, using digital terrestrial photogrammetry, the existing sculpture can provide features, whereas other data sources are required to determine the size, shape and location of missing features. The investigation involved creating the CAD model of a part of Anobanini Rock using digital photogrammetry as the basis, the documentation of the archaeology elements in the computer and the recording of other attributes of the Anobanini Rock.

Although the acquisition of some tape measurements was a component of this task to make a scaled model (land surveying is an important part of any project of this type), the accuracy obtained from the photogrammetric procedures was considerably in excess of requirements (RMSE 1.00 cm). It was determined that the desired accuracy could be achieved if:

1 the acquired data (photographs) was taken with a digital camera appropriate for terrestrial photogrammetry; the appropriate camera be calibrated for lens distortion, principle point and focal lens;
2 camera location and camera angles information used during the photography be determined;
3 an experienced photographer be responsible for photography;
4 object point locations be clear on the photography;
5 control point locations be clear on the photography; and,
6 known dimensions on the object, scale information, etc. were available.

Figure 5.10 shows a view of Anobanini Rock. A few dimensions were added to this figure when the author investigated the site.

FIGURE 5.11
A View of the Anobanini Rock at Sar -e Pole Zahab

5.5.2 Data Acquisition

For the 3-D model of the Anobanini Rock, the most significant features were acquired from terrestrial photographs using a digital camera. Data extraction from terrestrial photographs to create 3-D models depends on a number of factors such as: data type, data resolution, data quality, accuracy and representation.

Close-range photogrammetry was used for the documentation of the facets, to direct the archaeologist to adequately identify the conservation needs of the stonework. This must be done using approximately 1:50 scale photography for all the archaeological features. This integrated all stonework, inscriptions, epigraphs, etc. including visible damage, e.g. cracked stone.

5.5.3 Data Input

Probably this is the first time that the Anobanini Project provided data for input to the PhotoModeler Program (PMP). The data are then extracted from PMP and used in AutoCAD for the further processing towards building the A/AIS. The PMP procedures interactively construct the geometric base for the digital records of the A/AIS.

All photographs were imported into a directory (a Windows folder) and were then examined to eliminate the poor photographs and checked to ensure the required coverage of the object was achieved.

5.5.4 Processing

Processing the photographs was achieved with PMP. In PMP, the procedure of creating 3-D models starts with the connection of 3-D points, edges, curves, etc. As already indicated (see section 5.2.4), there are eight steps in creating a 3-D model:

- Create a camera calibration report,
- Plan the measurement of the object,
- Capture photographs of the object,
- Import the captured photographs,
- "Mark" the features on one photograph, that will be 3-D vertices (either control points, feature points or tie points),
- Identify the same 3-D vertices on the other photograph,
- Process data, and
- Export the results in the form of 3-D coordinate data for the vertices or orthophotos – for example to AutoCAD or ArcGIS.

The sculpture can be considered as a set of objects. For each object there were many 3-D object points to process. For example, in the left figure's headwear object, of a pyramidal and peaked design (the 'Anobanini Hat'), about 270 points were referenced. Once the processing was completed and the photographs were oriented, the orthophotos were generated. A sample of a created orthoimage is shown in Figure 5.11.

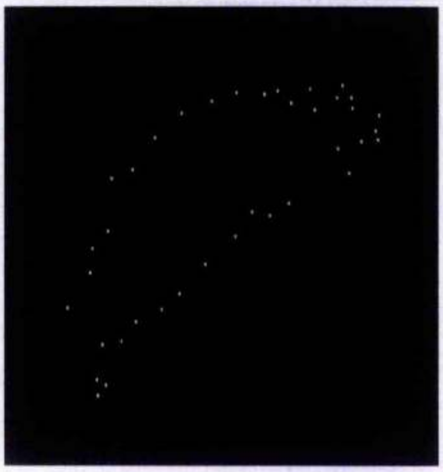
5.5.5 Linking: the Anobanini Project

DXF files can link different programs, for example Object Linking and Embedding (OLE) can be used. DXF and Text file formats support Running External Programs (REP) for an embedded link between different programs. An object created by AutoCAD can be used as an OLE object. A destination application creates the compound document that accepts OLE objects created with the program. The OLE links to one or more compound documents and exports the information to other applications. Many CAD and rendering packages, and others, such as AutoCAD and ArcGIS can import text, diagrams, digital photos and DXF data files for more detailed measurements in A/AIS applications.

Figure 5.12 shows a result for the A/AIS, an orthophoto of the head area in the Anobanini rock sculpture. The OLE capability exported the data to create the surface model from PMP to AutoCAD for further processing.

FIGURE 5.12

Fragment of Orthophoto of the Anobanini rock sculpture imported into AutoCAD, with selected detail digitized



The Anobanini sculpture is a surface rather than an object. It thus lends itself much more to the single surface approach of topographic DTMs. Indeed such a DTM would be ideal for monitoring or recreating the sculpture. Although a TIN model of the object's surface was created from interactively registered data points, and fitted the original well, a more realistic approach would have been to use automatic terrain extraction procedures (stereo-correlation) such as supported in SOCET SET. Looking to the future, the protection of such a rock sculpture might be better supported by laser-scanning as well as a photography archive. Modelling objects of this surface type can rely on well established 2.5 D GIS processes.

5.5.6 Surface Modelling

To satisfactorily visualize an archaeological object through raster graphics, a complete description of the object's surface is needed; this may require interpolation. In the Anobanini project a TIN was preferred because no more interpolation from captured vertices is needed for further processing.

AutoCAD reads all the coordinates of vertices, which have been stored already in a text file. 3DPoly establishes the connectivity of these vertices automatically, as closed polygons, to form facets (or planes) with the final point connected to the first one. The script file, *3dpoly.scr*, contains a list of all the planes of the object. All the vertices are stored as 3-D coordinates, with each set of these vertices representing a plane of the object. The resulting 3D surface model could then be rendered and enhanced.

There has been considerable recent work in developing efficient 'reverse engineering' tools which can take a point cloud and produce a surface (facet) model, but the author only investigated that provided by AutoCAD. For example, one of these (Cloudworx) uses the drawing tools of either AutoCAD or MicroStation to snap to the scanned (i.e. point cloud) points, thus making tracing accurate and works with the CAD dimension tools, to get exact measurements in 3D space, which is appropriate for remediation.

5.5.7 Data Extraction

AutoCAD is able to supply the data for different layers to illustrate the archaeological elements, damaged surfaces, etc. of a cultural object. The content of layers and their representation (e.g. colours, line types, etc.), and the operations between layers depend on the proposed applications.

The data extracted from PMP are raster, vector, or text data. Orthophoto extraction is proposed using the uncompressed *tiff* files. Vector data extraction employed DXF, in this project. In PMP, there are seven other output vector file formats available. Because of time limits, more extraction using other formats was not investigated. However, Appendix A shows a text file of 3D coordinate points of the 'Anobanini Hat'. Preparing a script file of the archived 3D coordinate points inserted into AutoCAD produces a measurable visualisation of the 'Anobanini Hat'. It is expected that the same holds for other components of the rock sculpture.

5.6 The Photogrammetric Survey of the Hunter Memorial at Glasgow University

The successful modelling of a cultural object implies that reconstructing the whole object becomes achievable. Digital photogrammetry techniques and digital facet modelling (involving representation of the object by facets instead of lines) combine the integration of the geometric and the pictorial characteristics of a building. Additional information is accessible through the "hot-linking" or equivalent facilities.

Unlike standard GIS with its focus on 2-D, CAD systems offer easy 3-D modelling capabilities [Sinning-Meister *et al.*, 1996]. Sinning-Meister *et al.* [1996] have advocated that a CAD system like AutoCAD is simpler than using a GIS environment in the architectural context. AutoCAD employed for architectural and archaeological purposes can support direct database access, just as can a standard GIS package. The elements of the relational database can be integrated with graphical entities like raster images and textual information. The output of digitised points can be supplied directly into AutoCAD. By using digital terrestrial photogrammetry the existing architectural features can be modelled, whereas other data sources are required to model the size, shape and location of missing features.

This investigation involved creating a CAD model of the Hunter Memorial, Glasgow University, using digital photogrammetry.

Although some tape measurements of the components of this monument were required to make an accurate model (land surveying is an important part of any project of this type), the accuracy obtained, by considering other check distances, was considerably in excess of requirements (suggested RMSE 0.40 cm; obtained RMSE 0.28 cm). Figure 5.13 shows the North Front view of Hunter Memorial. A few dimensions (tape measurements) are added to this figure. Measurements of this type can be used as check measurements or for scaling.

FIGURE 5.13

The North Front View of Hunter Memorial (Scale 1:50)

The Hunter Memorial was designed in 1925 by J. J. Burnet (Architect) with the collaboration of G. H. Paulin, (Sculptor). Portrait Medallions of the Hunter brothers can be found on the North Front view of the monument. William and John Hunter made names for themselves as anatomists. In APPENDIX B are some biographical details of the Hunters; such a text-file can be hotlinked to the model providing additional non-spatial information.

5.6.1 Data Acquisition

For the 3-D model of the Hunter Memorial, the most significant features were acquired from terrestrial photographs using a digital camera. It is important to carefully select the images to be used, because, in the approach chosen here only a small number of images can be processed. Furthermore, the usefulness for reconstruction of some objects depends on the orientation of the image relative to that object.

The camera used to obtain digital images was a Kodak DC4800 digital camera. The DC4800 is not an expensive camera, but the use of this camera offered a variety of resolutions for digital images. The specifications of this camera are:

- 3.3 megapixels resolution CCD delivering up to 2160 x 1440 pixel images.
- 1.8-inch LCD monitor and real image optical viewfinder.
- 3x zoom, 5.8 to 18.0 mm lens (equivalent to a 28 to 84 mm on a 35 mm camera).
- 2x digital zoom, power zoom with two driving speeds from 16 to 1/1000 seconds.
- Aperture options of f/2.8, f/5.6 and f/8.
- Image capture with JPEG and uncompressed TIFF file formats.

The photogrammetric system used was designed for the purpose of creating the basic 3-D models needed for monument documentation and computer reconstruction, within a potential A/AIS. Also the photography was used for the documentation of the façades, to direct the architects to adequately identify the conservation needs of the monument. This was done using approximately 1:100 to 1:200 scale photography for all the architectural features. This integrated all stonework, Portrait Medallions, columns, inscriptions, epigraphs, etc. including visible damage, e.g. cracked stones and mortar leaching. The survey was executed using digital photography taken around the object.

In multiple photo projects, each point or feature that is to be modelled should be visible on two or more photos. For this reason, the positions of the photographs need to be thought out. Thus, it is necessary to plan the photography and measurements of an object before data capture.

Nineteen digital photographs supported the Hunter Memorial project. All photographs were hand held (no tripod was used), but the camera axes were almost horizontal and nearly perpendicular to the monument at all exposures, unless they were oblique when the photographs were taken of the top view of the monument, from a nearby window.

5.6.2 Data Input

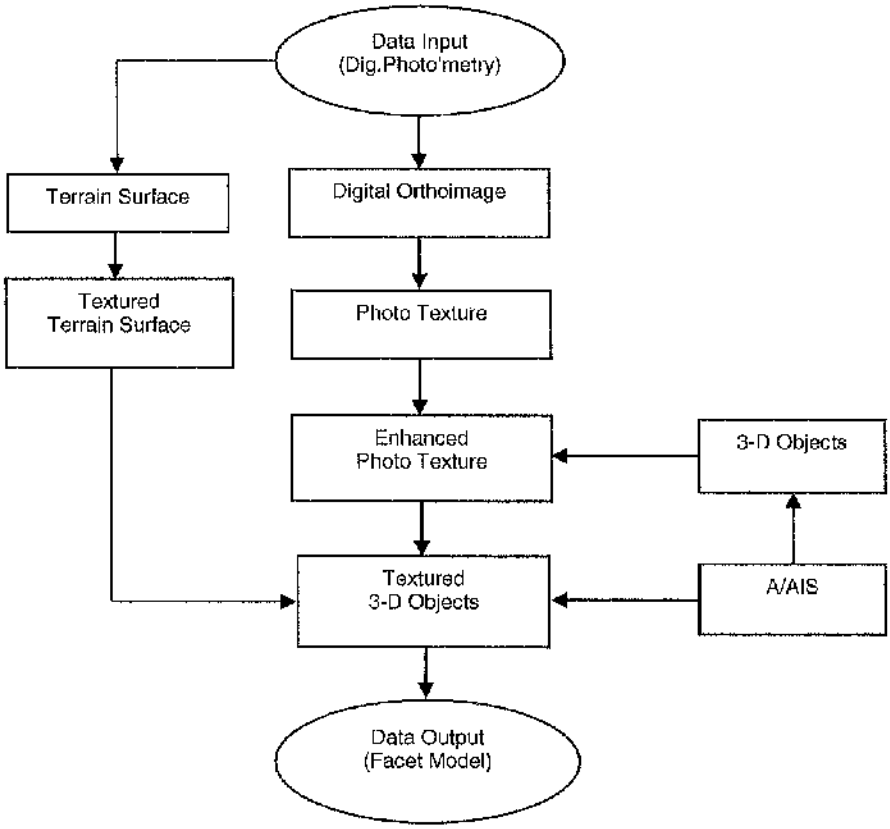
Probably this was the first time that Hunter Memorial provided data via the PhotoModeler Program (PMP)! The data were extracted from PMP and used in AutoCAD for the further processes towards creating the A/AIS. The PMP procedures interactively construct the geometric base for the A/AIS. Figure 5.15 shows the procedures in PMP and AutoCAD. It should be noted that many cultural objects are symmetrical and the same procedure can be used to reconstruct, e.g. the west part from the east one, by lateral inversion. Using systems such as those supporting CAD tools allows architects to model missing parts e.g. of one end the building and copy the appropriate part to the other end.

All photographs were imported into a directory (Windows folder) and then examined to eliminate poor photographs and also checked to ensure the required coverage of all sides of the object was achieved.

5.6.3 Processing

In moving from traditional surface reconstruction to automated systems, in which the human operator is the quality controller and editing manager, requires efficient interaction with 3-D data close to the specific application situation. The requirements of modelling terrestrial objects all point towards an increased use of automated processes to model the surface geometry and tools to determine non-geometric properties. For example, computer graphics and computer vision processes. Computer graphics calculates images from model descriptions, computer vision deals with the inverse process: the modelling of the object from images (for example, when presenting the results of a photogrammetric process or when rendering DTM data). If these processes are available close to the application site a computer model can be quickly generated to ensure adequate data capture.

FIGURE 5.15
A Scheme of Procedures for Developing A/AIS
(note: an expanded version of this diagram is found in Chapter 6)



Processing the photographs was achieved with PMP and the creation of 3-D models starts with the connection of 3-D points, edges, curves and cylinders. There are eight steps in creating a 3-D model with PMP:

1 Create a calibrated camera report;
2 Plan the measurement of the object;
3 Capture photographs of the object;
4 Import the captured photographs into the PMP;
5 "Mark" features on the photographs which will be 3-D points (control points, tie points and feature points);
6 Match 3-D points on the various photographs;
7 Data processing; and
8 Export the result of 3-D data to a CAD program.

As explained, any processing starts with camera calibration. In the Hunter Memorial project an approximate calibration for the DC4800 camera was used. After the camera calibration, the locations of features on each photograph were prepared.

To "*mark*" a point in multiple photographs indicates that a point can be determined in 3-D. When a point or a line is marked in several photographs, it is essential to insure (for PMP) that these are exactly the same points and lines. In the PMP documentation, a process called "*referencing*" identifies the points on one photograph of a feature as being conjugate to the points on the other photograph of the same feature. The PMP uses the "*marked*" photographs to create 3-D models through an interactive iterative process determining the location of points, and edges, in 3-D space.

After identifying and marking at least 3 points manually with the cursor (three points gives six equations, enough to solve for the camera orientation), the rest of the point identification is done automatically. Then a transformation of each point back into the image space is done, and the closest target in the image is chosen as the corresponding point.

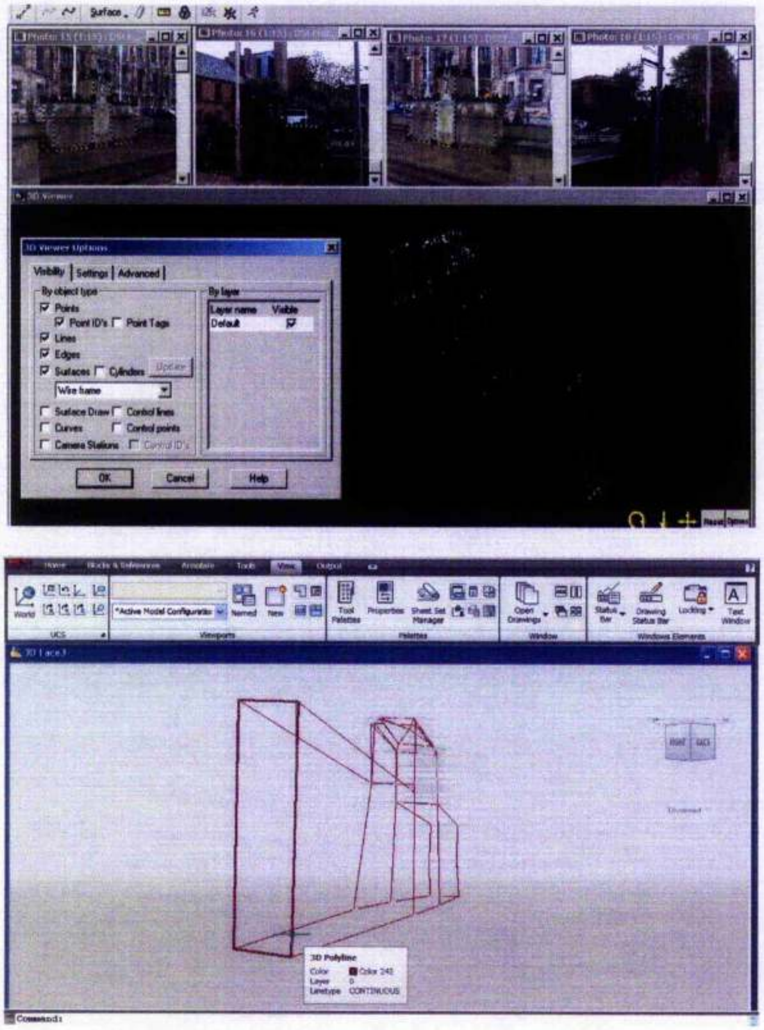
The amount of processing time depends on the number of photographs and the number of marked points. The four best photographs were correlated to create 3-D objects in this project. More than four photographs in an adjustment is prohibited in the interests of getting a good result in a reasonable time [User manual, Eos Systems Inc., 2000].

Figure 5.16 illustrates four overview photographs applied in this project in one adjustment, used to produce a simple 3-D model of the Hunter Memorial. The data are then transferred to AutoCAD. This took about three hours to photograph and process.

There were many 3-D object points to process (approx. 1200). For example, in the middle part of Hunter Memorial more than 120 points were referenced. Once the processing was completed, the photographs were oriented, and the orthophotos were generated.

FIGURE 5.16

Four Photographs Used for Producing an Overview Model of the Hunter Memorial



5.6.4 Mathematical Considerations

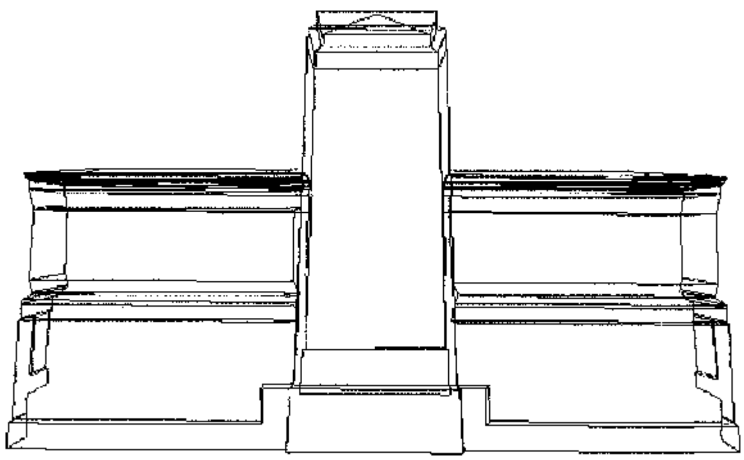
Some surface interpolating techniques do not fix the values of control points. Consequently, local characteristics may strongly influence the entire surface. Bézier and B-Spline mathematics use control points to define the shape of the surface, but only the B-Spline approach has the power of local shape control. The B-Spline approach is used in PMP. An advantage of using the B-Spline approach is the possibility of controlling the polynomial degree of the blending functions, independently of the number of control points.

5.6.5 Results

The first product was a wire-frame model of the monument, shown in Figure 5.17a,b.

FIGURE 5.17a

A completed wire-frame Model of the Hunter Memorial – north side and detail of north-east corner



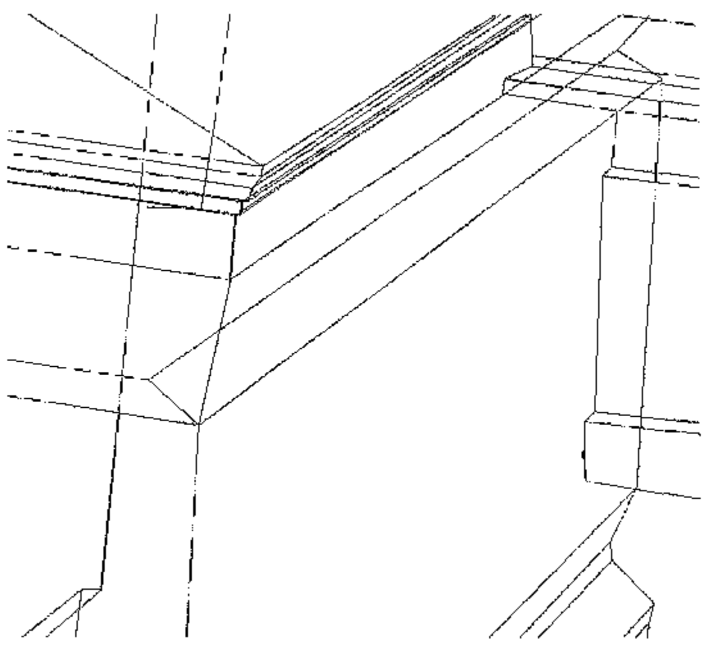
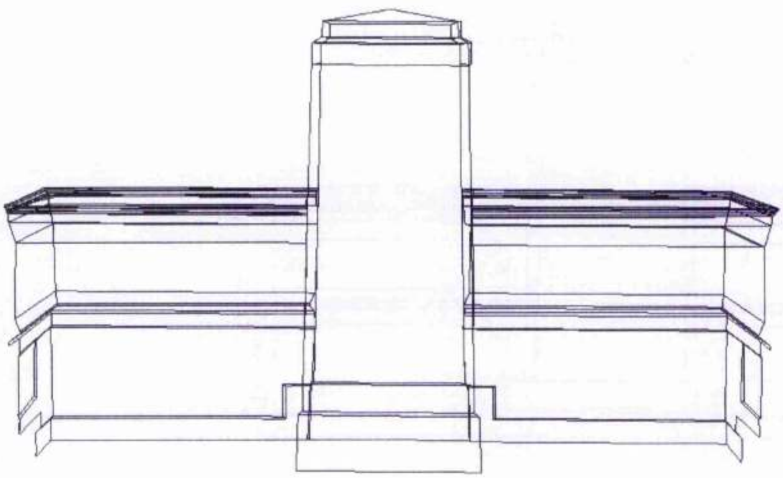
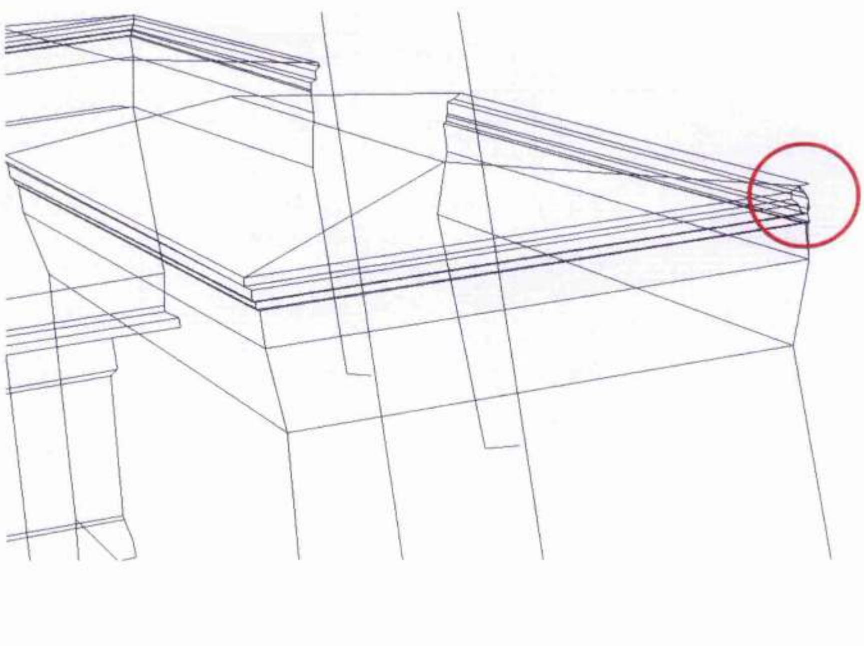


FIGURE 5.17b

A Wire-frame Model of the Hunter Memorial – south side and detail of north-west corner, also showing damage to masonry

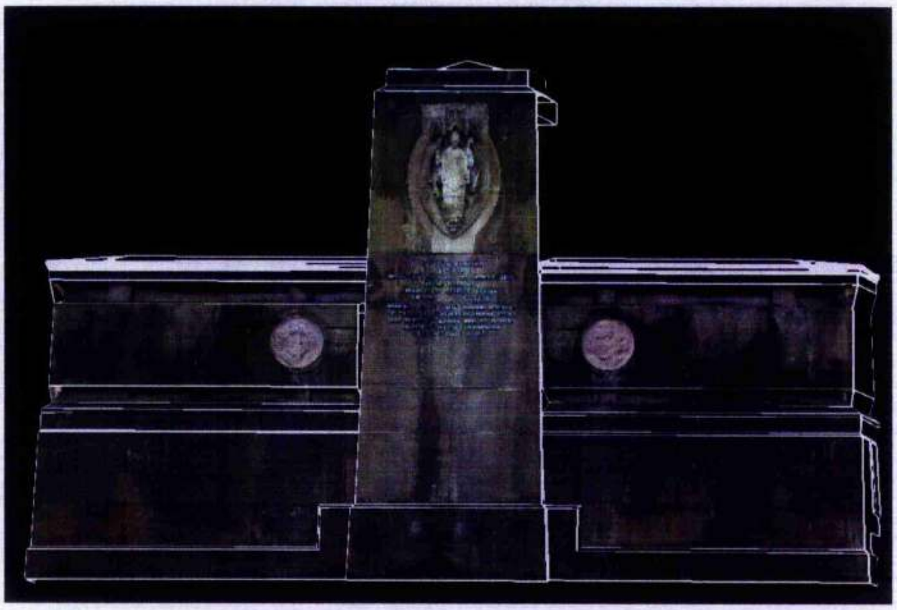




The second product was a rendered model of the monument, with orthophotos being used for the rendering. This is shown, in progress, in Figure 5.18. The OLE capability can export the created model to AutoCAD for further processing.

FIGURE 5.18

Orthophoto Rendering of the wire-frame model of the Hunter Memorial underway (upper) and completed (lower)



The author has determined that export files in the formats DWF, JPEG and 3DS can also be exported to the Web (in HTML file format) for downloading and regenerating images by others for future purposes. Figure 5.19 gives a result of integration between digital terrestrial photogrammetry (extracted from PhotoModeler program) and AutoCAD software in the form of wire-frame model. In this development, 3-D polylines are created and a part of this (as a sample) is presented in Table 5.6. All vertices can be examined as a script file, available in AutoCAD for further processing. The file may also be stored as documentation of this cultural object.

Figure 5.19

Wire-frame Model generated from information exported from PhotoModeler.

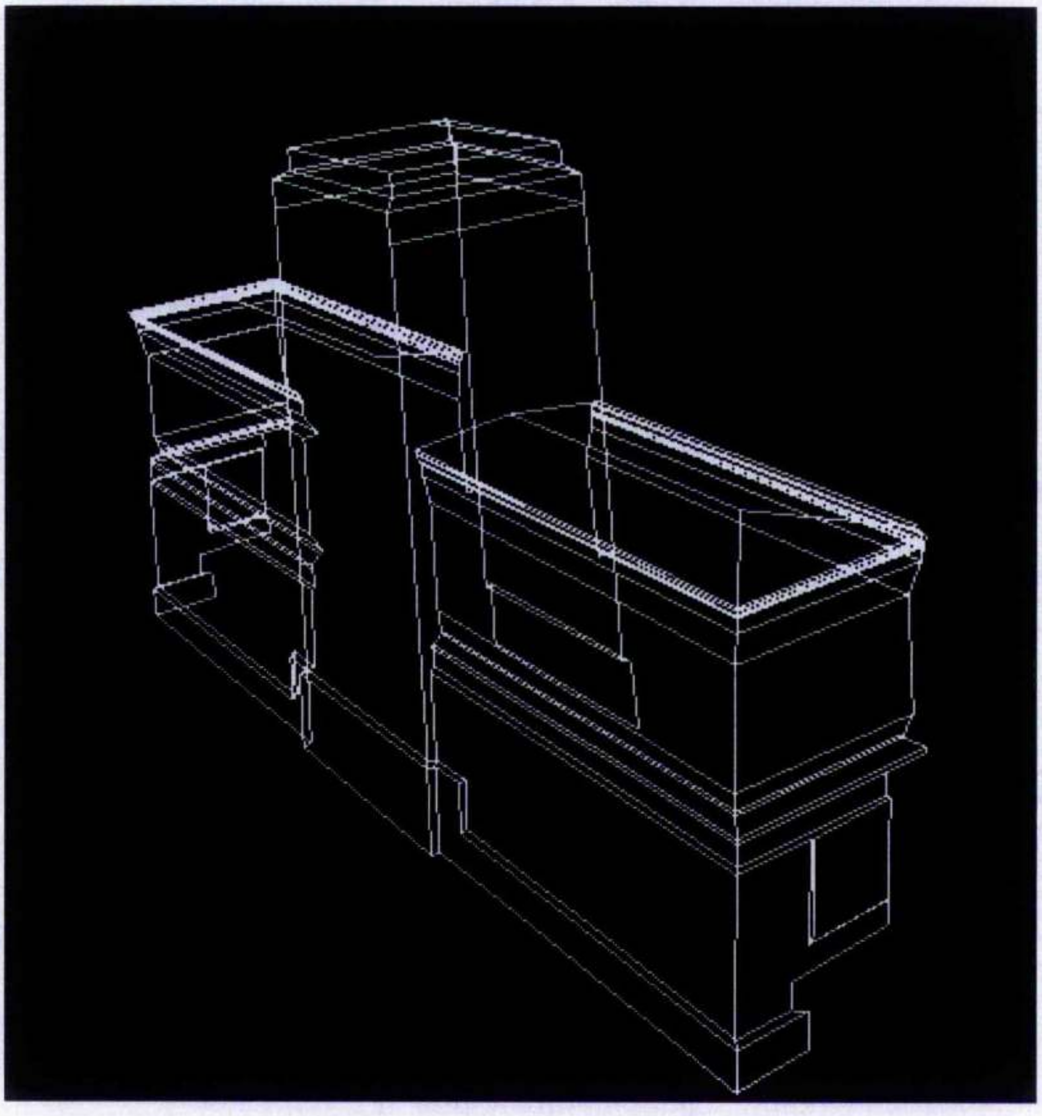


TABLE 5.4
Reported File of the 3-D Polyline for Facet Modelling, from PMP

POLYLINE Layer:"0"

Space: Model space

Handle = 437
Closed space
First 3 points did not define a plane. No area calculated.

VERTEX Layer: "0"
Space: Model space
Handle = 438
Space at point, X= 10.18 Y= 12.08 Z= -459.62

VERTEX Layer: "0"
Space: Model space
Handle = 439
Space at point, X= 10.18 Y= 12.08 Z= -459.62

VERTEX Layer: "0"
Space: Model space
Press ENTER to continue:
Handle = 43a
Space at point, X= 10.18 Y= 12.08 Z= -459.62

END SEQUENCE Layer: "0"
Space: Model space
Handle=43b

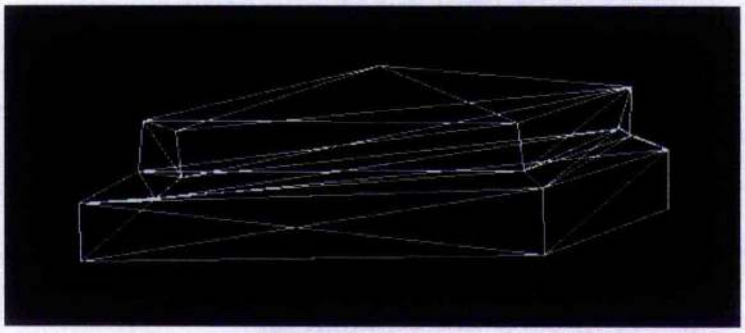
POLYLINE Layer: "DEFAULT"
Space: Model space
Color: 7 (white) Linetype: "BYLAYER"
Handle = 2a2
Polyface mesh

VERTEX Layer: "DEFAULT"
Space: Model space
Color: 7 (white) Linetype: "BYLAYER"
Handle = 2a3
Polyface vertex at point, X= 31.56 Y= -25.88 Z= -391.73

To visualize an architectural object, a geometrically correct description of the object's surface is needed. In this Hunter Memorial case a TIN was preferred because no more interpolation was required for further processing. A TIN representing the object's surface was created from registered data points fitting the original data exactly. Figure 5.20 shows the TIN for the cap of the middle column of the Hunter Memorial façade.

FIGURE 5.20

The 2-D TIN of Hunter Memorial Cap



5.6.6 Linking PhotoModeler data to AutoCAD

Common formats (e.g. DXF and Text files) are used to connect and integrate different programs; thereby Object Linking and Embedding (OLE) can be achieved. DXF and Text file formats support Running External Program (REP) for an embedded link between different programs, for example between AutoCAD and ArcView, SOCET SET, PMP and Excel. Thus an object created by AutoCAD can be used as an OLE object. A destination application creates the compound document that accepts OLE objects created with the program. The OLE links to one or more complex documents and exports the information to other applications. The AutoCAD REP facility can also be used to access more complex/specialised information, such as documents, texts, diagrams, photos, etc. Many other CAD and rendering packages can import text, diagrams, digital photos and DXF data files for more detailed measurements in A/AIS applications.

5.6.7 Accuracy

A method to ascertain the accuracy of a project is to use "*checking distances*" (i.e. check distances). Checking distances are compared with measurements for several items in a scene, obtained from the PMP. In this project, tape measured checking distances of several features were used. The results from the "checking distances" are given in Table 5.5.

Of course we are concerned with the quality of x, y or z coordinates as much as distances. Given a distance is obtained from two sets of triplets (x, y, z coordinates), then, assuming that RMSE of 0.7cm (see Table 5.5) has the same numerical value as standard deviation and that the error in x, y and z is the same, then error theory (propagation of variance) presents us with estimated coordinates standard deviation of $\sigma x = \sigma y = \sigma z = 0.28$ cm. This meets the accuracy requirements being sought of 0.41cm (see section 1.2).

TABLE 5.5
Checking Distances

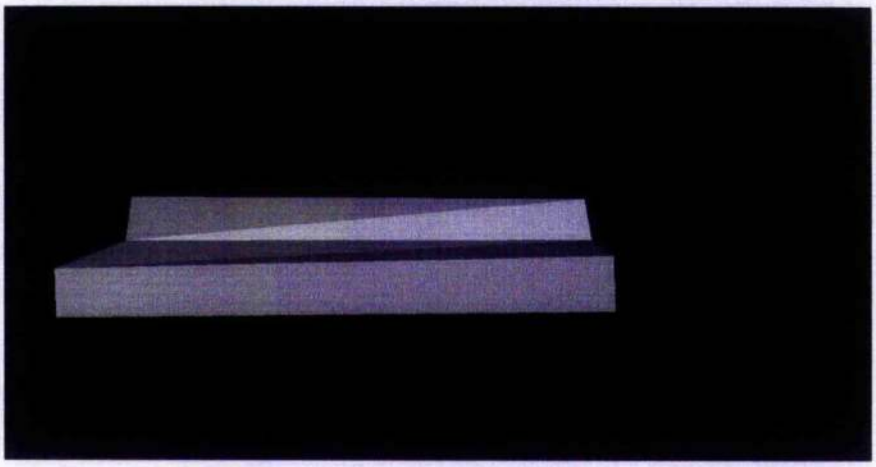
Ground (mm)	**Model** (mm)	**Discrepancy** (mm)
3715	3708	7
1415	1421	6
835	831	4
935	941	6
859	865	6
5185	5198	13
RMSE		**7**
Maximum discrepancy		**13**

5.6.8 Rendering

Rendering offers a technique for the visualization of digital facet models. To improve the impression of the surface model one can change the direction of illumination. Figure 5.18 shows the rendering of the cap of the middle column of the memorial. PMP can also export the camera station for those programs that support rendering. This is to identify where the camera is placed. Thus, the user can also view a rendered model from that camera position.

FIGURE 5.20

A Rendered Display of a Digital Facet Model of Hunter Memorial's Top



5.6.9 Data Extraction

PMP was able to supply the data for different layers in AutoCAD to illustrate the architectural elements, damaged surfaces, etc. The content of layers and their representation (e.g. colours, line types, etc.) and the operations between layers depend on the proposed applications. The different façades of the Hunter Memorial were processed individually for further development.

More information such as height layers and slopes can be extracted directly from the specified surface model and displayed as colour coded images. This can be used for monitoring different façades of the object.

5.6.10 Products

Texture maps are very important in (human) facial representation; poor texture seriously detracts from the realism of the image. It can be assumed that this is true for some other objects, too. A recently developed procedure, not investigated practically in the work reported here, involves texture laser-scanners. Texture laser-scanners are capable of collecting information on intensity as well as distance, resulting in a high-resolution surface with a matching high-resolution texture. Images scanned using a laser-scanner at a very high resolution can be rectified using photogrammetrically derived points' data [d'Apuzzo, 2005]. The DXF files, created by importing the photogrammetrically derived points data to AutoCAD can be used to generate the 3-D wire frame model and the laser imagery can also then add texture rendering to a 3-D digital facet model.

The data which can be exported from PMP are raster, vector or text data. Facet texture and orthophoto raster file export is proposed using the uncompressed *tiff* files, because of its widespread acceptability (e.g. it is the only format which can be 'hotlinked' to ArcView).

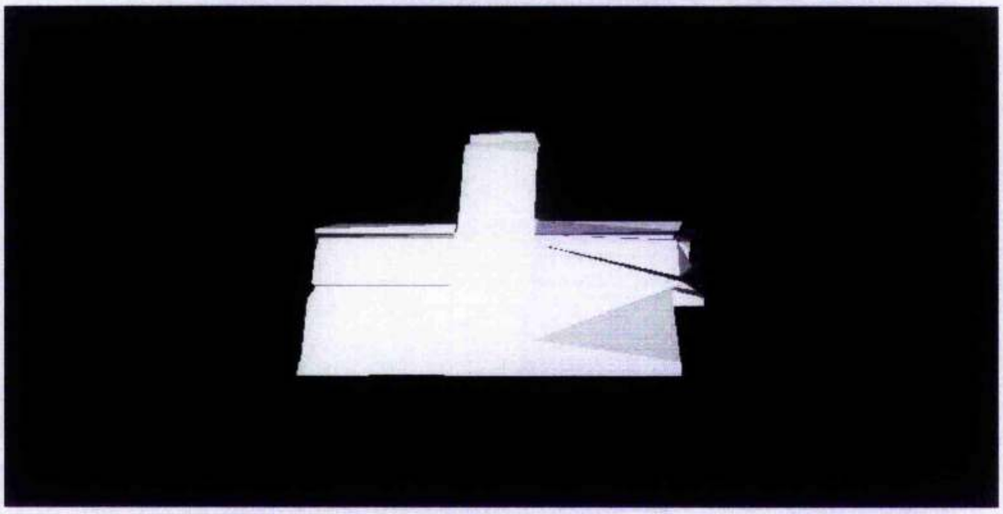
Vector data extraction employed DXF, in this project. In PMP, there are seven other vector output file formats available. The 3-D digital facet models created by PMP can be exported to another program, e.g. a CAD program. PMP generates its 3-D models in an arbitrary coordinate system. When a 3-D model is exported it will need transforming. The created models can be used in other programs with the following 3-D formats: *dxf, 3ds*, *obj*, *vrml*, *x*, *iges* or *raw* file. The AutoCAD program uses the DXF file format exported by PMP. The exported file can be manipulated and rendered using AutoCAD's tools.

PMP can export the 3-D data in a model projected onto a 2-D plane readable by a 2-D program. This ability can only be useful for planar surfaces, e.g. building elevation drawings. When 3-D surfaces are selected for export, the Face (i.e. facet) Texture Options become available.

An unsatisfactory attempt has been made to create an octree representation of the whole Hunter Memorial using the package 3D Studio (Figure 5.21). This arose from an investigation of free space description methods, which can contribute to octree building. The technique has two stages. The first is the decomposition into voxels that can either be 3-D primitives in a CAD system (using solid modelling) or holes in an object (or virtual subspaces resulting from the octree representation of volume spaces). The second stage is the management of structural or topological links between the voxels. The method involves sorting through a cloud of points and finding their surface topology based on selecting their nearest point. This may find surface holes or surface voxels of the object. It is assumed that improved photography, including camera calibration, of the Hunter Memorial might have improved the outcome of this investigation. But circumstances precluded acquiring new images of the memorial. For future work, the new results of octree representation can be compared with these so far obtained. A successful outcome would more readily have paved the way for full object modelling, rather than surface facet modelling.

FIGURE 5.21

Textural Extraction of Hunter Memorial for Octree Representation



Digital surface modelling (digital terrain modelling) provides input to produce a digital orthophoto of the object's surface. Since the orthorectification process is performed pixel by pixel at the orthophoto scale, a high resolution digital surface model is required. An orthophoto can be used in conservation, e.g. to determine of size and location of eroded and water damaged features.

5.6.11 Outcomes from the Hunter Memorial Case

This investigation provided 3-D details and orthoimages of the Hunter Memorial. The methodology used has created satisfactory results for recording the façades and for the monument's consequent restoration and digital analysis. The photogrammetric record using digital facet modelling can create a detailed and complete documentation of all the façade elements. The time spent to provide such documents was kept to minimum for all data gathering, processing and digital facet modelling as data output.

Reliable procedures have emerged in the Hunter Memorial investigation for the photogrammetric survey of architectural monuments, which make achievable the architectural drawing, and reconstruction of lost details of cultural buildings consistent with existing archived photographs.

5.7 Summary and Conclusions

Photogrammetric techniques bring many benefits to architectural recording. Bryan and Clowes [1997] indicate that photogrammetry prompts an excellent stereo photographic record of monuments, and provide a homogeneous level of recording across a whole façade or structure, being largely independent of the level of detail. They suggest results can be provided rapidly and in advance of other site works such as scaffolding. In comparison with traditional surveying and manual methods, a huge volume of primary data is captured and recorded quickly.

Likewise, it can be assumed, applications in the archaeological area can benefit.

Archaeologists require the creation of plans and sections. Much of this continues to be carried out by the traditional archaeologist's methods, such as placing a meter square grid over each area of excavation and graphically recording the detail, on taping features. But, rectified photographs are now becoming more commonly used across the archaeological field, and since the mid-nineties archaeologists have taken far more interest digital terrestrial photogrammetry [Dallas, 1996].

Although not a common application generally, Dallas [1996] states that terrestrial photogrammetry has now become one of the best-known applications of photogrammetric science in the specific fields of architecture and archaeology.

The five examples presented in the preceding chapter range from quite massive structures (St Avit abbey) to a rather small object (Hunter memorial). Remediation may require extensive repair (e.g. replacing a 50m x 20m façade) or detailed repair (e.g. recarving a stone medallion). Large structures will require a lot of photographs, so the software has to be able to process these; the author's investigations indicate that currently the low-end PhotoModeler is constrained in this respect. Extensive repair can be carried out using dimensions obtained from a digital orthophotomosaic archived with its digital surface model, as produced by a package such as SOCET. A digital orthophoto-mosaic of a façade mimics the traditional architect's elevation drawing, but offers a much richer source of measurements. Detailed repair, if it is (as may be likely) to involve automated machining will require high-resolution gridded 3-D data. Either a high-resolution orthophoto archived with its high-resolution digital surface model, of the detail, or a TIN generated surface (facet) model can be used to generate such a 3-D grid.

The solutions available to the author evolved during these investigations and will continue to do so. Currently, compared to SOCET, PMP seems more user friendly and less versatile but entirely adequate for small objects; both deliver the required accuracy and are summarised by project in TABLE 5.6.

TABLE 5.6 PROJECT ACCURACIES

Project	System	X,Y,Z rmse	Approx. Photoscale
Strome Castle	PhotoModeler (PMP)	10.0 mm	1:500
Gilbert Scott	SOCET Set	2.0 mm (best case)	1:60
Hunter Monument	PMP	2.8 mm	1:100 – 1:200

The five examples investigated in the preceding sections of this chapter are summarised in the following paragraphs.

In 1999, in a joint effort with GUARD (Glasgow University Archaeological Remediation Division) staff the author captured digital photos through a DC260 Kodak camera from an excavation at Strome Castle. Using PMP orthophotos, were produced, from which, it was shown, the outlines of the building stones could be digitized. This digital data captured from the orthophotography could be used to create 3-D wire-frame models for producing a 3-D visualisation of the castle.

The data set of St. Avit was gathered to provide an archive of stereo-photography of this important building and a basis to investigate different digital techniques, software facilities and instruments in order to obtain geometric and thematic information of a building, methods for recording, document retrieval and maintenance. A digital camera (DCS 420 Kodak) was used to record control detail, a terrestrial survey camera (UMK 10/1318 Zeiss) was used to provide stereo imagery of the object and a Zeiss theodolite (one second) was used to obtain the control points. Photoscales of 1:50 or larger were achieved. The digitised UMK data and control information were processed in SOCET SET. The data set was acquired for the 3-D modelling of St. Avit, in a CAD environment. Unfortunately this was not achieved. It is assumed that the homogeneity of the wall material prevented good image matching, and the Digital Surface Model of the wall did not present input of adequate quality for the hoped for mathematical modelling of the surface, which would have enabled architectural epochs to be identified.

The third example is from the Gilbert Scott Building of Glasgow University. Its photographs were taken by the UMK 10/1318 Zeiss camera and then digitised. In this case orthophotos of small components of the structure only were produced, such as carved medallions, using SOCET along with the relevant Digital Surface Model. These could be accessed from ArcGIS, via a simplified wireframe index of the building and hotlinked photographs of a façades for detailed measurement. A further investigation used PMP for Digital Surface Model generation, automated reconstruction, feature extraction and object modelling represented in AutoCAD, again of a selected small feature, a window arch.

A fourth project was investigated by the author at Anobanini Rock, which is located at Sar-E-Pol-E-Zahab in the North West of the Islamic Republic of Iran. The aim of this assignment was to investigate an existing photographic archive (most photographs were at about 1:50 scale, and were convergent) with regards to its ability to produce a 3-D surface model. This was achieved successfully for a component of the rock sculpture, the 'Anobanini Hat'. The photographs were taken by SONY DSC-F828 digital camera, which supplied data for the PMP package.

A final example was investigated, again from Glasgow University properties. This is the Hunter Monument that was photographed using a Kodak DC 4800 digital camera, to provide data for the PhotoModeler package (PMP). The Hunter Memorial is found near the main entrance of Glasgow University. In this investigation the author produced rendered 3-D models of the memorial achieving RMSE values of 0.28cm.

The successful completion of the fifth project demonstrates the usefulness of establishing an archive of photography of cultural objects, gathered at an appropriate scale and with sufficient overlap and control for data extraction using a low end package such as PMP. The management of these photographs and other documents related to the cultural objects is well handled in a corporate spatial database management system, i.e. a GIS. The documents, each belonging to their own project, can be indexed spatially through simple 3-D models, and processed either using GIS tools or other linked packages.

The major contributions of the investigations reported in this chapter include recommendations for the representation of spatial information, the appropriate architecture for a system and development of procedures for camera data capture. The results of the evaluations discussed in this chapter show:

- the possibility of integration of digital photogrammetry, CAD and GIS;
- the possibility of upgrading data to document changes;
- the possibility of accessing and handling data from different users; and
- the possibility of data exchange with various existing systems.

6. Building the Information System

6.1 Introduction

This chapter discusses the establishment of an Architectural/Archaeological Information System (A/AIS), in the light of the author's findings.

In Chapter 5 it was indicated that a choice was available and a B-rep based A/AIS could be established either in a commercial GIS package such as ArcGIS/ArcView or in a CAD package such as AutoCAD. At the local scale 3-D visualisation (which usefully presents 3-D models of real world objects [Reed, 2000]) is commonly seen as a function of a CAD package, such as AutoCAD, and allows researchers to analyse 3-D objects. Some of these analyses are, however also, made possible by standard tools supplied by the GIS. As shown by the author in Section 4.3.3 and by the work of Wadsworth and Treweek [1999] GIS can be used as a modelling tool and for spatial analysis in the field of building documentation.

It should be noted that for many years, ESRI (the developer and supplier of arguably the most popular series of GIS packages) marketed a product, ArcCAD, that provided GIS functionality within AutoCAD, rather than the other way around. It is only now, with the emergence of the latest generation of ESRI products (ArcGIS/ArcView 9) that full CAD functionality is found within a GIS environment, as an add-on. But it should be noted that AutoCAD is so well established amongst Civil Engineers and Architects, that this package is still likely to be the environment of choice for the 3-D modelling of cultural objects (particularly large structures), albeit extended by GIS 'approaches'.

As indicated in Chapter 5, it is possible to link programs such as ArcGIS and AutoCAD – running one program from the other. Given that there are those who advocate GIS as a corporate Information System, one can think of the GIS as supplying an 'index', via a simple 3D model, to documents, large scale orthophotos of a cultural object, and a link to a CAD package where detailed 3D modelling takes place.

In this work, the author determined that to establish a simple 3-D model in a standard GIS package (e.g. ESRI's ArcView) without a costly add on, requires that for each facet 3-D coordinates, or triplets, of each object point appearing in two facets must appear in two input files. This is shown in TABLE 6.1, where there are two example input files; the highlighted points are common and are part of the roof (one facet) and the south wall (another facet). Photogrammetry is an obvious source for these coordinates, either from a digital photogrammetric package (such as PMP) or from an orthophoto interrogated in ArcGIS. Having obtained these coordinates points, the subsequent processing to form a 3-D model within the selected GIS environment (ArcView) and developed by the author, is as follows, for each facet:

Step 1.

Produce a closed 2-D polygon for each building facet, in the appropriate format. In the ESRI environment this involves:

- producing a POLYGON coverage (e.g. SOUTH) for each facet, using CREATE, GENERATE (e.g. input SOUTH.TXT) , CLEAN, BUILD;
- adding the coverage of each facet as a THEME to the PROJECT (e.g. STATION) and VIEW reserved for this facet's processing (e.g. SOUTH-FACET); and
- converting the coverage to a 2-D shape file (e.g. SOUTH).

Step 2.

Import a point field file for each building facet, in the appropriate format and create a TIN. In the ESRI environment this involves:

- adding the depth file (e.g. SOUTHDEP.TXT) as a TABLE to the project (e.g. STATION) and as an EVENT-THEME to the view (e.g. SOUTH-FACET); and,
- using SOUTHDEP.TXT to create a TIN (e.g. SOUTHTIN).

Step 3.

Create and display a 3-D polygon of the facet (eventually with other similar facets). In the ESRI environment this involves:

- o using SOUTH and SOUTHTIN create a 3-D shape file of the facet (e.g. SOUTH3D); and,
- o adding SOUTH3D to the 3-D Scene Viewer (e.g. STATION-MODEL).

TABLE 6.1

3-D Facets' Points for ArcView Import

```
SOUTHDEP.TXT
   depth,       xcoord,       ycoord
000014.50,    0012.185,      01.250
000014.95,    0002.364,      01.435
000014.95,    0002.485,      08.451
000014.70,    0007.632,      10.325
000014.50,    0012.843,      08.642
ROOFWDEP.TXT
   depth,       xcoord,       ycoord
00014.95,    0002.485,      08.451
00014.70,    0007.632,      10.325
00004.60,    0007.317,      10.766
00004.80,    0002.432,      08.646
```

At this stage, the connected facets of the building appear in the 3-D viewer as a three-dimensional object, which can be rotated. These steps (1 – 3 listed above) can be repeated for the remaining facets, resulting in a 3D screen display (such as in the example of Figures 4.7, 4.8). As shown by the author, this will produce a simple 3-D model of a building (although complexity can be increased by including more facets, as in Figure 4.9). To this can be linked other documents such as a large scale orthophotos of building details which can be examined, even digitized, for greater detail within ArcView, or other packages.

Despite the development of this three-step process, the author's findings were that 3-D modelling in this standard GIS environment is less user friendly than using CAD (i.e. AutoCAD). There is a need to consider coordinate systems and transformations between them; a facet coordinate system may be that in which the data are actually gathered using the digital photogrammetric workstation but for model building there will have to be in a common local coordinate system. Beyond that, if there is a national archive of photographs of cultural objects, then a national WCS may be likely to be required, and transformation of some details (for example camera station coordinates) to this system may also be needed.

See Figure 6.1a for an overview of these approaches with regard to GIS, and Figure 6.1b with regard to CAD.

FIGURE 6.1a

A Proposed Integration of Digital Photogrammetric and GIS

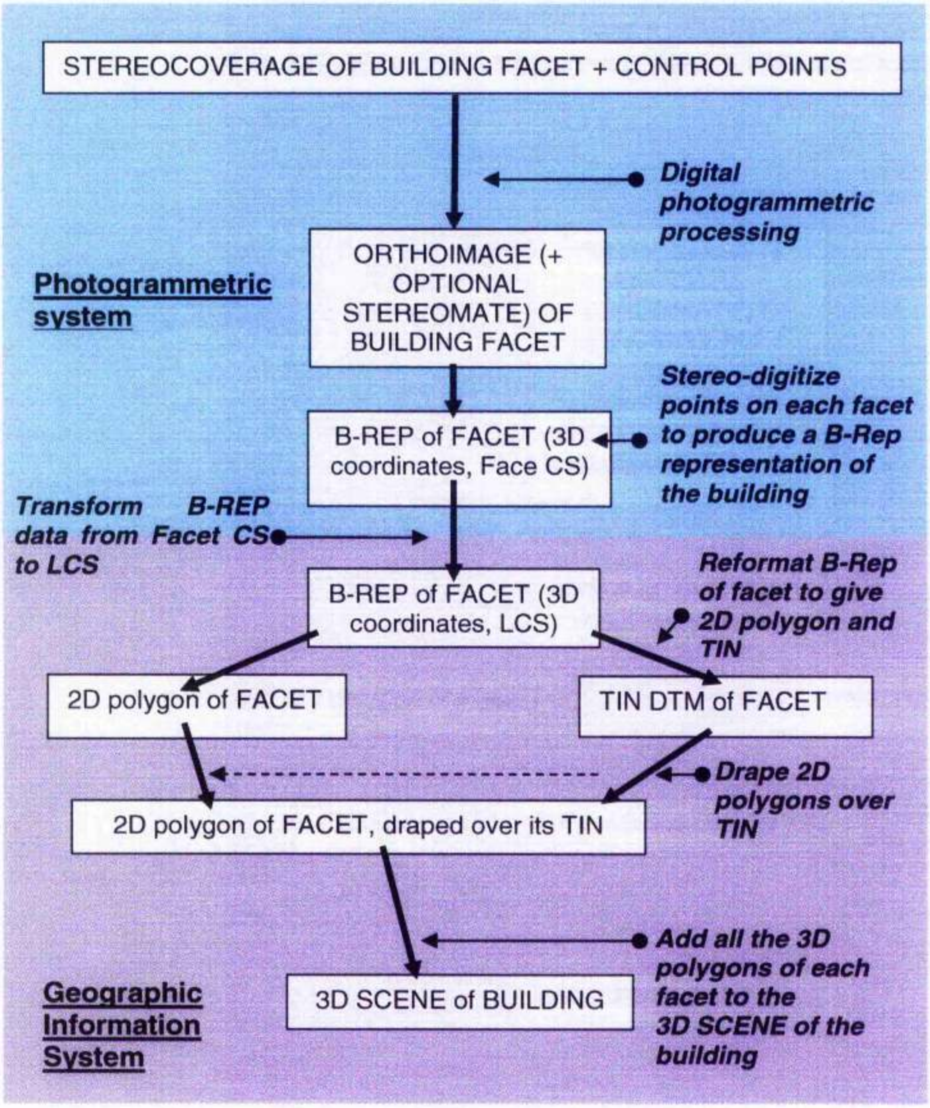
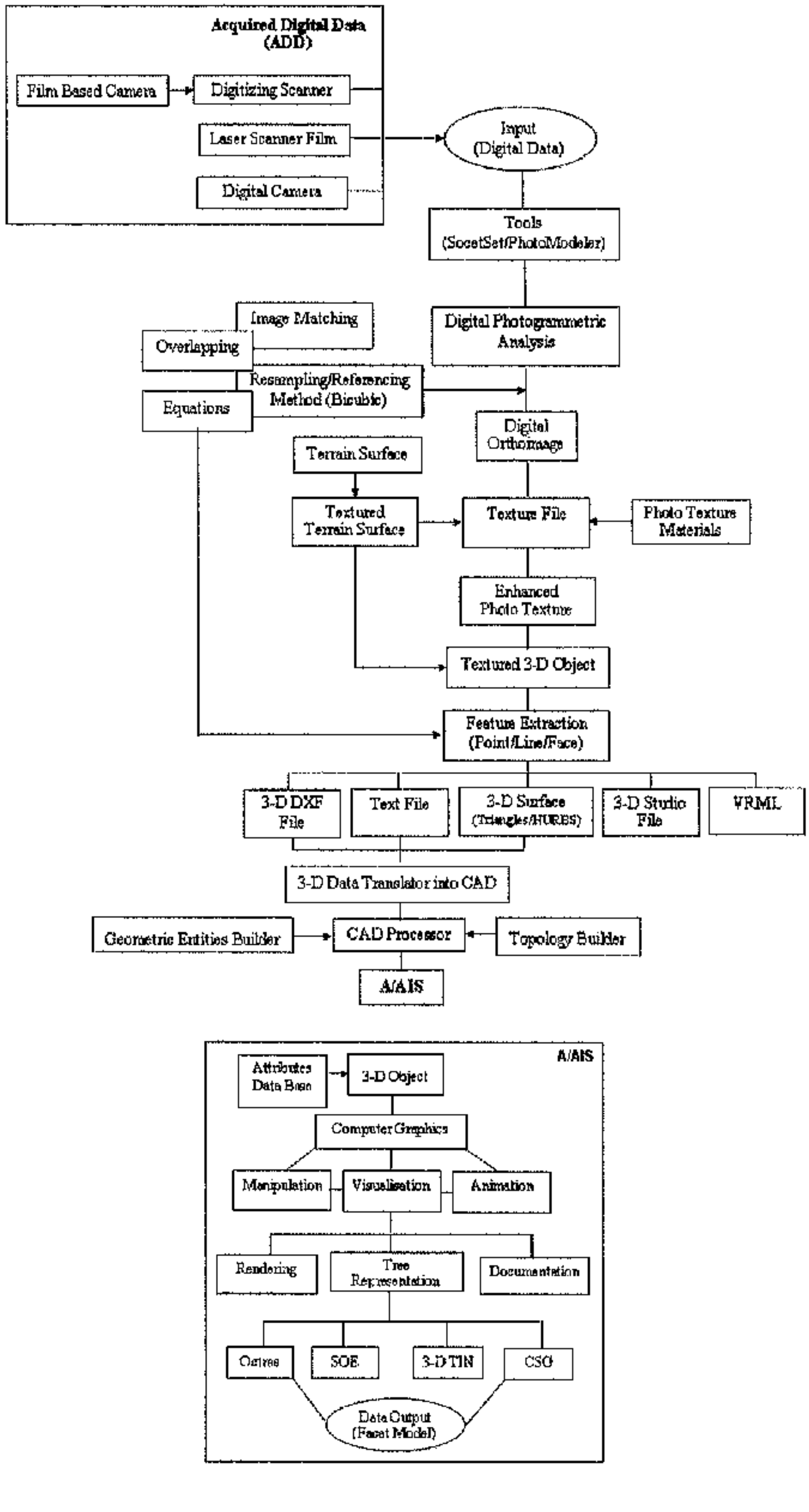


FIGURE 6.1b

Integration of Photogrammetry and CAD



6.2 Combination of GIS and Digital Photogrammetry

Despite the many years of development outlined in Chapters 2 and 3, which have resulted in the B-rep approach becoming standardised in CAD packages, within geospatial research in general, 3-D modelling remains problematic. Comprehensive treatment of the problems can be found in Molenaar [1998] and more recently in Zlatanova, Abdul-Rahman and Shi [2004].

Photogrammetry may be the best of the currently available 3-D measuring techniques from the point of view of providing documentation (i.e. orthophotos) as well as measurement. Not all researchers are equivocal on this (alternatives include the traditional: land surveying and tape measurements, or the most novel: laser-scanning) depending on relevance, accuracy, controllability, standardisation, performance and economy. The required quality and quantity affect costs. Photogrammetry may be cost effective when applied to the management of cultural monuments, nevertheless the author found photogrammetric data capture exacting and time consuming.

The GIS 'approach' to spatial data management makes possible the integration of data capture by digital photogrammetry and modelling by CAD. Following the specific investigations of Chapter 5, this is addressed, more generally, in the following section.

6.3 Three Dimensional Modelling and GIS 'Approaches'

GIS is a powerful tool for anyone who is engaged in any kind of engineering, planning, industrial purpose, product development, geospatial research, etc. GIS has powerful visualization tools using any integrated data. But, CAD packages such as AutoCAD automatically generate 3-D feature models and place them in a dynamic 3-D visualisation. In addition, the parametric feature modelling capabilities found in AutoCAD offer texture management enhancements and the ability to generate digital panoramic images for use on Web sites and for other purposes.

As indicated, it is the powerful integrating capabilities of GIS, which are attractive in archaeological and architectural work. However, AutoCAD has other useful tools, so if it too could 'integrate' then it might form a better basis for the A/AIS than a more standard GIS package.

3-D modelling is well developed in a few sectors, such as oil exploration and plant management. These sectors typically use more powerful platforms and have more skilled software developers than those available to architecture and archaeology. Standard, off-the-shelf, low-end GIS packages do not, so well support 3-D modelling as CAD, but in the investigations reported in this thesis, digital photogrammetry has helped to capture the data to develop 3-D models of spatial objects such cultural monuments. Both SOCET Set and the PMP Package have been used in the projects referred to in this thesis to extract the 3-D data, for 3-D models, from digital or film-based photographs. For example, data captured from an object through a digital camera and processed through PMP was transferred directly as data files to a GIS. The photographs were archived as photographs needing further processing and as orthophotos available for further measurement. The user of such a system can re-evaluate the photographs/orthophotos, selecting those to be used, at will. In either case the appropriate processing or measurement software can be accessed from a standard GIS.

Stereoviewing

Producing topographic surface models from stereo-images has been an active research and development topic for the last eighty years. Stereo viewing of images has been the most common method used by the mapping, photogrammetry and remote sensing communities for elevation extraction, until recently – when automatic image correlation took over. For extracting important points, interactive stereo viewing of images is likely to continue to be important. Stereo viewing of matched imagery allows the quick and accurate gathering of data to form the model, its quality assessment and the interactive editing of the model. In the work carried out by the author stereoviewing was supported in SOCET set only, not PMP. When using PMP the author had to exercise extreme care that correlated points in two photos were correctly identified.

Although not investigated in this work, some enterprises now are developing add-on tools for well-known GIS systems which support stereo-viewing of aerial images. An example is ISM's PurView, acquired by ESRI and released by them in 2005 "a plug-in that converts ArcGIS Desktop products into advanced stereoscopic image-viewing and feature-digitizing environments" [ESRI, 2005]. Although, at the moment only being applied to aerial images, possibly such tools can be adapted to handle terrestrial images.

6.4 Two and Three Dimensional IS

The author has found the B-rep approach to 3-D modelling better supported by standard software than any other approach. In this approach, an object is decomposed into facets, each represented as bounded polygons, which contact each other along edges stored as 1-D lines and curves, which in turn are formed from connected up vertices, or 0-D points. Each facet is a single surface.

A true 3-D structure has many surfaces and will contain multiple z values at the same x, y location and thus be able to fully support volumetric calculations. Both a terrain grid and a Triangulated Irregular Network (TIN) are used in the GIS environment to create and represent a single surface, such as the surface of a farmer's field, generating the so-called 2.5-D model. The approach described in Section 6.1 of this chapter combines several such surfaces (one for each building facet), in a GIS, to create a 3-D model, but without further application development, is very time consuming.

As already indicated, the TIN structure represents a surface as contiguous non-overlapping triangular elements. A TIN is created from a set of mass points (or a point field) with x, y, z coordinate values, which can be obtained photogrammetrically. TIN surfaces are frequently created by performing a Delaunay Triangulations (DTs) of all the completed points. DTs create a series of triangular areas that touch their neighbours at each edge.

TIN offers many advantages for surface analysis. First, the density of sampled points and therefore the size of triangles can be adjusted to reflect the relief of the surface being modelled with more points sampled in areas of high variability or available data. Second, they incorporate the original sample points, providing a useful check on the accuracy of the model. Third, the variable density of triangles means that a TIN is an efficient way of storing surface representations. Fourth, the data structure makes it easy to characterise the surface to build up cultural monuments' façades.

ArcView can use the TIN approach to model surfaces identified by the user. Thus if a cultural object consists of, e.g., five more or less planar surfaces (perhaps four walls and a roof) a TIN can be used to model the variations across each individual surface. In this implementation TIN cannot cope with multiple surfaces as there may be (e.g.) two points with the same x,y coordinates but different z coordinates (a floor and a roof point, for example), or two points with the same y,z coordinates but different x coordinates (a point on an east wall and a point on a west wall for example). In PMP the TIN approach is also supported and in this case also multiple surfaces, however the author found the TIN approach supported by PMP very sensitive and introduced irregularities in what were, effectively, plane surfaces bounded by many (>3) points. For clarity this TIN approach may be referred to as 2-D TIN, because the 3-D TIN approach (sometimes referred to as 3-D TEN), which is based on tetrahedra rather than plane triangles can simultaneously model more than one surface of an object. In the TEN approach a 3-D solid (i.e. object) is represented by correlated but non-overlapping tetrahedra [Qingquan Li and Deren Li, 1996] [Abdul-Rahman, 2000]. Parts of a single tetrahedron (which itself has four faces and four vertices) may belong to two surfaces, thus both the inside and the outside of a building can be easily and simultaneously represented. In geological applications it can model many surfaces [Carlson, 1987]. But more importantly it is a solid modelling approach which can honour the data points captured from all photographed surfaces. The TEN approach was not supported by Photomodeller 4 (the version used by the author) and so not examined, but it is expected it will be in the future.

6.5 Model Generation and Objects

Digital modelling is preceded by an abstraction of the real world. This abstraction transforms the human observation of this real world into a nominal model classifying the properties of the world that are relevant for the proposed uses of the digital model. The nominal model directs the implementation of the digital model.

Practically, in the context of the work carried out by the author, establishing the normal model involved identifying the facets (façades) whose nodes were captured.

6.5.1 Data Input to the A/AIS

In the work reported in Chapter 5, input data consisted of nodes describing the spatial attributes and references of all 3-D object points. Data input to the A/AIS was simple text files or specially formatted text files. These data, including DXF files assist the user embed or create a link between different programs, i.e. ArcView, SOCET SET, and AutoCAD. In the case of AutoCAD the Running External Programs (REP) facility could be used for presenting complex/specialised documents, texts, diagrams, photos, etc., and for auxiliary data capture.

With input being achieved by the author in SOCET or PMP, labelling information was also arranged such that an object was naturally and clearly described. Each node was labelled with an integer node number. Nodes formed edges. All edges had a minimum defined edge length because of two 3-D object points (nodes) having a minimum separation distance.

6.5.2 Model Building

Data are collected from overlapping photography using three different approaches. Individual points' x ,y, z coordinates can be extracted a) directly using a digital photogrammetric workstation, b) from 3-D models formed by stereo orthophotos and their stereo mates, or c) from the orthophoto with its associated digital surface model in the GIS. In this project the author used the first approach (a).

As implemented by the author, the first step in model building using digital photogrammetry was camera calibration. Each camera needs its own description. This description consists of data on focal length, imaging scale, image centre and lens distortion and can be stored (for example in the A/AIS) to be associated with the relevant photographs. Any change of lens and sensor requires a new calibration to be made. Thus a record of all relevant calibration data was retained, to be applied with the relevant photography if further photogrammetric processing was needed.

It was noted by the author that calibration in PMP is much easier than in SOCET, and that for non-topographic photogrammetry (that is the approach being used in this work) the camera used could be calibrated using PMP software, even if the subsequent processing was in SOCET.

The next step in model building was identifying features on the individual digital photographs as they appeared on the screen. The important features had to be visible in at least two photos. The author attempted, while taking photographs to identify the facets requiring eventual modelling and to ensure ideally three (but at least two) views of each facet were completely captured. It was easy to discover occlusions in the photography, which required more photos to be taken.

The data processing steps which led to the extraction of the 3-D coordinates of a model's points using digital photogrammetry consisted of two stages. The first stage returned feedback to the user on how well the exterior orientation adjustment (referred to as 'orientation' by PMP). The second stage ran a number of algorithms to create the 3-D models. When the initial measurement and modelling were completed, further work on the model could be achieved by adding more points and lines. The completeness of the model could be quickly checked by examining a simple wire-frame model. Once the 3-D model was as complete as required, it was saved and exported.

6.5.3 Extraction of Scaled Detail

In PMP defining a scale for the captured data was achieved by indicating the known length of a marked line in a photograph. In SOCET this was achieved through the more rigorous manner of control points in an appropriate 3-D coordinate system.

Control points or lengths can be acquired by GPS or total stations, or other methods of ground surveying. In this research, a variety of techniques was used, including surveying using 1" theodolites and taping. This latter was partly because of the author's experience in north-western Scotland in the late 1990's when GPS derived control was unreliable, and multipath arising from castle walls was a potential problem, and at St Avit where again the massive nature of the building presented potential multipath problems and most of the measurement was performed internally, precluding the use of GPS. In documentation of cultural objects, particularly buildings, these problems will almost always arise. (Control points used for the Gilbert Scott building are in Appendix D.)

Attributes were collected as well as geometry. Attribute data capture can be undertaken directly in the field by a data logger or manual keyboard recording, or from photo interpretation. The author obtained such data either from photo-interpretation or from archival sources.

6.5.4 Accuracy

By archiving orthophotos and their surface models, but having them accessible through simple index models, measurements of a cultural object can be obtained at any time in the A/AIS. The accuracy of a measurement made using orthophoto procedures depends on:

- the quality of the calibration of the camera and digitiser;
- the resolution of the camera and digitiser;
- the geometry of the camera positions;
- the precision of marking/identifying the object features that appear in the
- images;

and

- the resolution of the generated orthophoto.

For data acquired with the high-resolution cameras, e.g. Kodak DCS, and processed with reasonable care, PhotoModeler has demonstrated a relative accuracy in linear dimensions of around 1:2,000 with 95% probability. With higher resolution medium format metric cameras or high quality digital cameras accuracies as high as 1:10,000 are expected; lower resolution cameras and imprecise marking can reduce the accuracy to 1:500 [Eos Systems, 2000].

The developers of PhotoModeler have introduced a circular sub-pixel target [Eos Systems, 2000]. Using the sub-pixel target marker greatly improves the precision of marking. If other factors are taken care of (good geometry, good camera calibration, etc.) one can achieve 1:25,000 or higher accuracy in a project that is substantially all done with sub-pixel target marking.

A relative accuracy, e.g. 1:2,000 means that for an object with a 10m largest dimension, PhotoModeler can create 3-D coordinates with 5mm accuracy at 95% probability. In the author's work on the Hunter Memorial a maximum error of 1.3cm was achieved.

All imaging devices have limits of resolution. The light ray coming from some feature on the object and intersecting the imaging media can be distorted by both the lens and the imaging medium. The higher the resolving power of the imaging system (lens and media), the more precisely will it be possible to identity where that light ray hits the media. Consequently, a high resolution CCD is better than a low resolution CCD; but most CCDs have lower resolving power than most film. Through the projects executed by the author the camera's resolution gradually increased.

Finally the quality of data capture off an orthophoto will be reduced if the resolution of the orthophoto is deliberately selected to be coarse (perhaps to save storage space).

6.5.5 VRML, X3D

To visualise the generated model the photogrammetrically derived data can be converted to VRML (Virtual Reality Modelling Language). VRML is a format for 3-D data which supports features such as hierarchical transformations, light sources, viewpoints, geometry, animation properties and texture. The conversion to VRML is fully automatic and consists of two parts: geometry conversion and texture mapping. In the geometric part the object coordinates and the topology information are converted. The texture mapping is performed with an eight parameter image rectification for each face of the object. When there are more than four points bordering a face the eight parameters are determined through a least squares adjustment. For only three points in a face, the projective transformation is approximated by a six parameters. The investigation of virtual reality packages for modelling cultural objects was not an objective of the investigations reported on in this thesis. However they could be part of a future research agenda for those considering the modelling of cultural objects for remediation purposes. PMP has the ability to export VRML files

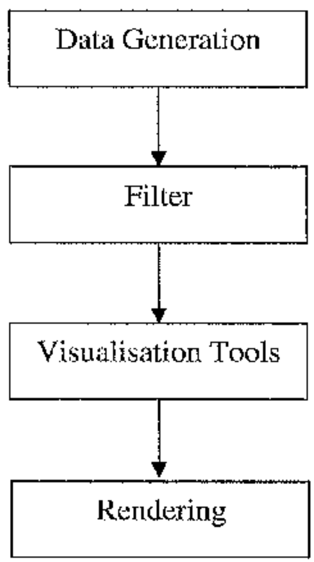
VRML began to be used when HTML was emerging, but it faced many limitations. With the popularity of XML, the VRML specification has been recently rewritten to take advantage of programmer familiarity with XML [Dethe, 2005]. The resulting specification, X3D, is governed by the Web3D Consortium, which provides open-source tools, examples, and documentation. Like VRML, X3D allows high-quality 3D rendering in real time. X3D has not been examined, practically, by the author.

6.5.6 Graphical Representation

Graphical representation (visualisation) is very important. Any field of application, which has to deal with large data sets, has been met with the problem of the visual presentation of the results. For archaeological and architectural visualisation effective rendering is essential. The processing flow for this task is shown in Figure 6.2.

FIGURE 6.2

Basic Processing Flow (Algorithm) for Rendering



Foley [1990] classifies the multitude of rendering algorithms which have been introduced in recent years into:

- ray-tracing;
- volume rendering; or,
- 2-D and 3-D texturing.

Ray tracing has not yet been considered in this thesis. The ray-tracing algorithm allows photo realistic image generation, including transparency effects. The scheme is to trace rays from the eyes of the simulated viewer back to the illuminating light sources. This must be done for each image pixel. If the ray intersects an object, it will be converted into a reflected ray or if the object is not solid into a transmitted ray. Rays represent light and shadow. This process can be slow, and formats such as X3D do not require it [Dethe, 2005].

The automatic data transfer of a photogrammetrically generated digital surface model to CAD provides a flexible three-dimensional geometric object description. The CAD system is suitable for documentation and visualisation, as well as complex simulations, manipulations and analyses of the object.

The accuracy with which a geometric model of an object needs to be created depends on the application. When an object is to be visualised and rendered, the accuracy must deal with the detail by which surface properties are known. The photographic detail of a building facade may have no more geometric detail than an ellipsoid for a human face or a cube for some other generalised object depicted on a cultural object. Yet, the cultural visualisation may require the low geometric detail be accompanied by high levels of detail pertaining to colour and material. In this case rendering using orthophotos becomes advantageous, as executed by the author for the Hunter memorial.

Visualisation and rendering gives the user an occasion for analysing objects at a later period for planning and controlling restoration. In addition, computer-assisted photogrammetric methods are able to provide a relatively quick reconstruction of cultural objects. The photos of objects and their detailed interpretation supplemented with relevant text information results in an integrated archaeological and architectural archive.

6.6 Application of GIS

Three processes using GIS contribute to the conservation effort:

1. Monitoring change in details;

2. Measuring an orthophoto (for gathering new 3-D coordinates); and,
3. Modelling a structure (from historical or archived orthophotos).

With a GIS such as ArcView a project is created and the orthophotos of the cultural object with supporting digital surface models are added to it. Then the 3-D coordinates of selected points in the cultural object can be found off an orthophotograph for 3-D modelling, as described in Chapter 3.

However a further check of the morphology of the model is also important, because even if coordinates are 'within spec' misaligned edges are misleading.

In addition, a set of check dimensions can be created, prompting questions such as: Is the accuracy of the model adequate? GIS application development environment (ADE) tools established using AVENUE (the PC ArcVIEW ADE) or VBA (ArcGIS/ArcVIEW v8 or v9 ADE) can answer these questions, objectively. If the answers are inadequate, procedures (such as orthophoto regeneration and 3-D point capture) can be repeated.

6.7 Feature Extraction

Simple features are vector objects of the types: point, line, or polygon; they lack "intelligence" or connectivity. Simple feature datasets are useful because they are easy to create and store. They can be retrieved and rendered on screen very quickly, but connectivity (i.e. topology) is required for 3-D model building. Thus, an A/AGIS requires more than just features described by their coordinates and texture. Features with established connections to other features are required in GIS. This may be referred to as topologic structuring. Topologic structuring forces all line ends that are within a user-defined distance to be snapped together so that they are given exactly the same coordinate value. A node is placed wherever the ends of lines meet.

Orthophotos can also used to extract a planar texture for use with (a face in) a rendering program. For example, a rendered building looks much better if a component (i.e., a brick) is a realistic one derived from an orthophotograph of itself mapped onto its walls.

6.8 Data Formats

This section summarises the author's experiences with regard to data formats. An important consideration in translating CAD data to or from a GIS, is data format. Whereas some GIS programs make direct use of CAD formats, many employ a unique proprietary file format. CAD files must be translated to this format before the GIS software can process them. This translation process can be accomplished directly or indirectly.

3-D data output can be based on the raster, vector or text data models. For face textures and orthophotos the export of uncompressed *tiff* raster files is common, and moving data from SOCET to ArcView used this. A common vector data format is .DXF. Some of the (now growing number of) accessible output files for PMP are in the formats: TEXT, DXF, IGES, RAW, WAVEFRONT, VRML, DIRECT3D AND 3DSTUDIO. The first four are vector format, and the last four are for raster data output.

To date, the vector data model has been very widely implemented in GIS. This is because of the precise nature of its representation method, its storage efficiency, the quality of its cartographic output, and the availability of functional tools for operations and analysis.

Many CAD programs manipulate and render 3-D models, but what constraints are there with regard to data formats? For example, most of these programs will accept at least one of the file formats exported by GIS software.

PhotoModeler exports data in 3-D file format such as the Drawing Exchange Format (DXF), 3-D Studio and VRML. Then the 3-D data can be exported on a plane as 2-D data, which can be transferred as 2-D DXF file formats. But a graphic package such as AutoCAD has the potential of using 3-D data extracted from PhotoModeler for further use.

The DXF file format is supported by virtually every 3-D package and therefore is a good format for sharing geometry. However, it is limited in the type of data it can transfer (i.e., texture maps and fully-defined materials cannot be exported in a DXF format). DXF is, of course, a vector data representation.

The vector approach parallels the traditional (pre-computer) approach to representing buildings and monuments, i.e. the architectural plan or elevation drawing. Thus for ensuring that the traditional approaches of architects are mimicked by any suggested replacement based on digital photogrammetry plus CAD/GIS, it may be important to capture an area object in vector form, specifying the locations of the points that form the vertices of a polygon as necessary. This seems simpler and much more efficient, anyway, than a raster representation, which would require listing of all of the cells that form the area.

To create a precise approximation to an area in raster, it would be necessary to resort to using very small cells and the number of cells would rise proportionately and inconveniently. But, in common GIS applications, the apparent precision of vector data is often considered unreasonable, since many geographic phenomena simply cannot be located with high accuracy. Therefore, although raster data may look less attractive, it may, in common GIS applications, be considered a more honest reflection of the inherent quality of the data, especially given that various methods exist for compressing raster data that can greatly reduce the capacity needed to store a given database.

A surface can be represented as a TIN (thus vector) or as a GRID (thus raster). The former is likely to be truer to the original data and require less storage space than the latter. The latter may support many more GIS processes, but they may not actually be required in the management of cultural monuments. The simple 3-D GIS modelling of a building in ArcView implemented by the author used TIN. Nevertheless, most modern GIS packages will support transformation from the TIN to the GRID format.

6.9 Summary and Conclusions

GIS software can produce simple 3-D models that can be likened to work in the fields of both CAD and image processing.

In a CAD system, object entities are represented symbolically as simple point, line and polygon vectors. But this basic CAD data model has three severe problems for most applications at geographic scales. First, CAD models typically use local drawing coordinates instead of real-world coordinates for representing objects. Second, individual objects do not have unique identifiers it is difficult to tag them with attributes. Third, CAD data models are focused on graphical representation of objects and they do not store details of any relationships between objects (e.g. topology) where that type of information is essential in many spatial analytical operations.

The second type of simple GIS 3-D model is derived from work in the field of image processing. In this type of model, the main data source for geographic image processing is scanned terrestrial photographs, orthophotos and other digital images. It is natural that GIS supporting this geometry model would use raster or grid approaches to represent the objects and their rendering. The image data model is also well suited to working with pictures of objects such as photographs of monuments and scanned cultural buildings that are held as attributes of geographically referenced entities in a database.

The present chapter has considered building a 3-D GIS. Because of the convergence of the GIS and CAD environment, the author has shown that an information system can be supported by a CAD package (such as AutoCAD) or by a GIS package (such as ArcGIS).

7. Conclusions and Future Work

7.1 Introduction

In this concluding chapter it will be beneficial to quote the original aims of this work, as stated in Chapter 1:

> "While the general aim of this work will be met through investigating appropriate projects and relevant full or partial A/AIS implementations, this process can contribute to Geomatics in general if two particular objectives are achieved, namely:
>
> 1. to create digital models of cultural objects capable of supporting analysis in the chosen environment; and,
> 2. to specify the data content of digital images required for such models.
>
> "On completion of this investigation, it is hoped that the potential augmentation to the documentation and conservation of 3-D cultural objects (e.g. statues, monuments, archaeological relics, etc. but primarily buildings), supplied by the data capture functionalities of digital photogrammetry and the modelling and *quantitative spatial analyses functionalities of GIS, will have been considered (i.e. identified and assessed) sufficiently by the author.* This will enable him to be able to contribute to the development of well-founded systems for the archiving, interpretation and processing of photographs, documents and other data recording Iran's rich cultural heritage."

What has been achieved in this study? With exception of those in italics, the above aims have been achieved, and this final chapter will help show this. On the one hand completed tasks will be considered and on the other contributions to the archaeology and architecture sectors will be identified.

7.2 Completed Tasks

In general terms, within the past decade (1995 – 2005) considerable progress has been made with regard to increasing the IT and other new technology facilities available to archaeologists and architects in terms of decreasing costs and increasing effectiveness. For example, new technology now allows the surveyor to transfer digital data directly to the relevant database from survey or photogrammetric instruments, and in an appropriate format for the management and interpretation of the resulting 3-D data in one of several information system environments, such as can be created in AutoCAD, ArcView, etc.

This has been demonstrated in this study. For example 3-D data and facet based orthophotographs, gathered and generated in PhotoModeler used to produce a rendered 3-D model of the Hunter Memorial have been successfully transferred to AutoCAD. Scaled 3-D models of the Hunter Memorial, have been generated from these data, in AutoCAD. AutoCAD supports a variety of 3-D modelling tools supporting reverse engineering; for the Hunter Memorial this has been demonstrated In the event of damage or loss, full or partial reconstruction of the memorial would be supported.

AutoCAD supports links between its graphic features and other documentation, enhancing the reverse engineering potential. In the case of the Hunter Memorial the other documentation was only an example, namely biographical details of the Hunter brothers, but this could have been documentation obtained from archival sources concerning the memorial's construction.

Links are also supported between AutoCAD and other packages such as ArcGIS/ArcView – this environment being the conventional GIS environment. Also links exist between PhotoModeler and ArcGIS/ArcView. (These links are detailed in Figure 6.1b).

Having successfully demonstrated these links one must consider their value. GIS provides excellent spatial data management tools and a variety of spatial visualisation and analytical tools. However the GIS package examined by the author does not, in a standard form, support 3-D spatial analysis and its 3-D visualisation tools are time-consuming to use (i.e. without the production of new application tools). Thus one of the original aims (restated at the start of this chapter) "*quantitative spatial analyses functionalities of GIS*" has not been exhaustively investigated with regard to the 3-D models of archaeological or architectural objects.

One reason for this (although a facet based 3-D model of a small building was implemented in ArcView this was not spatially analysed) is the absence of easily implemented 3-D models in GIS. This is an area for future research and the author has concluded that, under current circumstances it is the spatial data base management tools of GIS which are important to the archaeology and architecture sectors. Spatial data, text and image files can be imported into, indexed, selected and exported out of a GIS

For monitoring and maintaining historic monuments archaeologists and architects need precise information. As demonstrated close range digital photogrammetric techniques (supported by, e.g., PhotoModeler) provide the means to do exactly that, particularly with respect to the spatial information, by allowing 3-D coordinates of photographed features to be accurately gathered, with a precision of about 0.4cm, and archived. This greatly enhances the flexibility of data usage, allowing it to be translated and interpreted in many different forms, including output as drawings or as 3-D CAD models (for example using AutoCAD).

7.3 Guidelines

As already stated, this work's two general aims were:

- to create digital models of cultural objects capable of supporting analysis in the chosen environment; and,
- to specify the data content of digital images required for such models.

Considering the first of these general aims, analysis may be carried out for a variety of reasons. It may, for example, be to identify different epochs in the construction of St Avit Abbey through noting changes in the curvature of the building's walls, which was unsuccessfully carried out in this work. More importantly analysis may be carried out for reconstruction or repair. Considering a building, there are many features which can be modelled as regular planes, and the work reported here has successfully addressed this; the 'guidelines' presented below review the methodology developed. There are features which can be represented by other regular geometric forms: cylinders, cones, etc., and these were not examined in this work. Analysis of the gathered data describing regular features will permit the recreation of appropriately dimensioned stone blocks, etc. for reconstruction. Finally there are detailed irregular features, such as the medallions of the Hunter Memorial or the Gilbert Scott Building.

In the event of reconstructing such detailed features a skilled stonemason may carry out the task using traditional means, solely by referring to large scale photographs of the detailed features, and such photographs also need to be gathered.

Alternatively a deskilled approach may be taken where a precise and high resolution digital surface model is used to guide the stone carving through an automated proces. Any approach taken which fits a regular body (plane, cylinder, cone, etc.) through captured surface points is, of course, completely inappropriate. In this case a solution based on generating a digital surface model from a dense collection of automatically extracted surface points would be appropriate. Stereo-image correlation as supported by SOCET SET or the use of a dense set of points gathered from laser-scanning would provide the necessary data. Apart from hotlinking a larger scale image of a medallion to an ArcView layer based on the photography of the Gilbert Scott building this aspect of an A/AIS has not been examined in the work reported in this thesis.

Considering the second of this work's general aims ("to specify the data content of digital images required for such models"), guidance is required for future work in this area. The practical methodology for using digital terrestrial photogrammetry in sites of archaeological and architectural interest depends on the position, shape, size, dimension, accuracy required and location of the object.

More specifically the following guidelines have emerged from the author's investigations:

1 A camera (film-based or digital) mounted on a tripod or hand held is adequate to capture the photographs of the object of interest. Particularly when a film camera is used, because of the delay in getting the photographs developed, preplanning is necessary. The preplanning will involve identifying camera stations and camera

rotation angles. Using a tripod more easily ensures the preplanning is adhered to. With a digital camera, coverage can be verified immediately, thus a tripod is less of a requirement. The St. Avit photographs were interior photographs, therefore needed longer exposures; tripods avoid camera shake during longer exposures.

2 Take the photographs at an appropriate distance from the object. Architectural plans are traditionally at the scales 1:50 or smaller. Mapping quality control convention would be to have photography at the scale of 1:150 to achieve this. The UMK camera had a focal length of about 100mm, implying an object to camera distance of 15m, to produce 1:150 scale photography. In the projects reported here the object to camera distances ranged from about 5m to about 30m.

3 Make sure the photographs cover all required object detail in stereo. In practice PhotoModeler requires that any photograph used in modelling has significant content found in at least two other photos, also. Once 3-D model building commences and if, unfortunately, occlusions are obvious, then using digital cameras allows the gaps to be quickly filled, but if the photogrammetric work is taking place at a distant location this is not possible. Thus careful planning before or during photography, of the facets to be captured must be carried out, to ensure complete stereo-coverage.

4 Obtain photo control by using a 1" theodolite and a tape measure graduated in millimetres, or equivalent. For a photo control located at a high level, some means to ease observations is suggested. For example, in the St Avit project, there were several beautiful and complicated figures on the ceiling which acted as good untargeted control points; a prism was added to the end of the telescope for better observation of these.

5 Scan the photographs at 25 microns/1000dpi or better, or directly acquire digital photography at a similar resolution.

6 Import the digital data into the selected software for processing.

7 Complete internal orientation, with an RMSE less than 1 pixel.

8 Complete external orientation, with an RMSE less than 1 pixel, or equivalent.

These eight proceeding guidelines ensure fast, comfortable and reliable data acquisition and processing, a requirement of any proposed system as stated in Section

1.3 of Chapter 1, where the tasks outlining the investigations to be reported on in this thesis are first presented.

9 Process the digital photography to provide a 3-D model and orthophotography.
10 Export the 3-D model or 3-D coordinates and orthophotography to the A/AIS.
11 Build the 3-D model in the A/AIS.

These three proceeding guidelines ensure visualisation appropriate to conservation tasks and simulate architectural and archaeological features within a full or partial A/AIS Information System. These are requirements of any proposed system as stated in Chapter 1.

12 Build the attribute database in the A/AIS
13 Link further photos, orthophotos, digital surface models and documents to the objects
14 Use orthophoto measurement software allowing further 3-D coordinate data to be added to the A/AIS

These three guidelines augment the GIS with additional 3-D coordinates, textual information and other information on the architectural entities which is a requirement of any proposed system as stated in Section 1.3 of Chapter 1, where the tasks outlining the investigations to be reported on in this thesis are first presented.

Close-range digital photogrammetry is proposed as a measurement technique for consideration when objects are fragile or inaccessible. These considerations were met in several tasks in the period of 1999-2005, investigated by the author. It also appeared that the only method to monitor dangerously cracked historical buildings is remote measurement survey.

Monuments and historical buildings most affected by earthquake and fire are often the oldest structures in a city. Some of these structures are the most culturally significant and must be maintained and documented as a valuable part of the heritage. Parts of buildings may be deemed unsafe and in need of demolition and rebuilding, but often no plans of the structure can be found, especially for ancient and complicated castles and religious buildings. A good intention is to create models of monuments as they appeared before they became damaged, but a photo archive is needed to support this.

7.4 Comparing the Methods of Object Representation

The thesis considered many techniques for representing 3-D objects and the relevant mathematics, in Chapter 2. These are important tools for building an A/AIS. The proposed system can be deemed to have been constrained by the drawbacks of existing software. SOCET SET and PhotoModeler software were specifically applied in data capture and ArcGIS/ArcView and AutoCAD investigated for building the 3-D models and databases..

For example, PhotoModeler software uses the TIN approach to create a 3-D wire-frame, from points, as the basis for its 3-D surface model. The alternative points based method for extracting a 3-D wire-frame from oriented photos in PhotoModeler such as Patch, Loft, Sweep, Revolution, Boundary Patch, Point Cloud and Cone Mode nevertheless do so via an intermediate TIN approach. Consequently even a plane surface may look 'bent', if insufficient care is taken.

Only the gathering of single data points in PhotoModeler is fast. If a B-rep approach is taken to gathering data, i.e. facets are identified and their bounding points joined to form polygons (thereafter called 'boundary patches' by PhotoModeler), then very satisfactory orthophotos can be produced in PhotoModeler for rendering a wire-frame model (see Section 5.6.5). Although rather slow, this does allow the user responsible for gathering the data from photographs to ensure that a satisfactory result will be achieved when the data are transferred to AutoCAD or ArcGIS/ArcView. The user of photogrammetric software ideally understands the categories of 3-D Points, Lines and Surfaces and that these can be exported to, e.g., AutoCAD for the enquiries of archaeologists and architects.

Another consideration in this thesis has been octree representation. It is the author's expectation that this provides a convenient means of visualising deformation, and it is his hope that this can be investigated in the future. Reliable conversion to and from octree representation is a topic for further investigation.

7.5 Conclusion

According to the introduction investigations resulting in appropriate procedures for surveying and documenting cultural objects are an intended outcome of this thesis. For example, even in the very recent past, manual measurements and direct copying of photographs of friezes onto transparent foil have served well. Manual 3-D processing of terrestrial images using analogue photogrammetric procedures is slow and may result in little information. In addition, it is a very time consuming task and requires the expertise of qualified personal.

Historic objects need to be documented without physical contact, either because of inaccessibility or fragility. The photographic method of data acquisition takes only a few minutes per photo and therefore it is possible to gather the data in a day.

Digital terrestrial photogrammetry permits rapid data recording at low-cost relative to other techniques (and particularly with the advent of digital cameras). For example, in a small project such as the Hunter Memorial Project (presented in Chapter 5), capturing digital data, data processing, recording and documenting of the cultural object can be done within a day or two.

Terrestrial Photogrammetry is not a new method to record and document buildings and monuments [Csáki, 1990]. In 1930, Gast used architectural photogrammetry to document the mortuary temple of Rameses II on the Nile at Thebes, Egypt.

The increasing accountability of managers of historical buildings for their conservation, throughout the world, requires reliable techniques. A hierarchy of photographic records (larger scale for fine detail, smaller scale for structural elements) is suggested based on the experience gained during a photogrammetric survey, which was part of an architectural investigation of the Hunter Memorial project in Glasgow University. It is important to identify records that are primary in the sense that they contain the maximum quantitative and qualitative information about the monument sites. Some photos will be used to produce a small scale model of the object, to which a variety of documents and scripts can be linked. Other larger scale photos can produce precise coordinates of fine detail (such the medallions and rosettes on Glasgow University's buildings).

Thus 3-D geometric data for the generation of geometric representations in an information system can be acquired by digital photogrammetry. The software interface between digital photogrammetric processing and CAD or GIS systems make it possible to transfer the acquired 3-D digital data, captured using digital photogrammetric software by measuring either the original imagery or the orthophoto (with stereomate), to the CAD system and use it to create 3-D wire-frame models forming the basis of the solid models used to produce the 3-D visualisation of the cultural objects.

The user is also able to perform the whole reconstruction of the 3-D objects without manual measurement, except that necessary for control. The automatic data transfer of the photogrammetrically generated digital surface model to the CAD system gives a flexible 3-D geometric object description to the GIS environment. Also, given IT's rapid progress, the author believes that the best results have not yet been reached.

The major contributions arising from the investigations reported are the identification of a low cost but reliable system capable of extracting high quality 3-D coordinates from photography to create a digital surface model, capable of guiding monument monitoring and maintenance, in a CAD or GIS based information system.

Thus to summarise the results of the reported investigations show:

- the possibility of an integration of digital photogrammetry with modern planning tools such as CAD or GIS;

- the possibility of documenting changes and augmenting the geospatial database as changes arise;
- the possibility of the integrated management of data pertaining to cultural objects; and,
- the possibility of data exchange between various existing systems.

Several projects have been investigated, large numbers of pictures taken and much time spent, but it was worthwhile, because it was completely impossible to gain as much useful knowledge without testing the proposed system. It may seem uneconomical at the first sight, but the obtained results and especially expertise gained contradict this.

7.6 Future Work

In this work digital photogrammetric techniques have made a very significant contribution to the design of an A/AIS; it is assumed that the flexibility and accuracy of digital photogrammetry will continue to benefit archaeology and architecture.

Digital facet models, which enable the representation of cultural objects by their surfaces (instead of lines) can be visualised pictorially through raster graphics. With respect to the high-resolution digital imagery, it was a goal to represent the architectural objects in the research. This research presents some experiences with the possibilities of facet models and the visualisation of architectural objects, but further investigation is needed to ensure the digital recording of highly detailed features.

Referring to the rapid development which has occurred in the handling of digital data in the last 10 years, it can be predicted that data derived from digital cameras, will completely replace the film-based photographic data. But also looking to the future the cost effectiveness of the photogrammetric approach advocated here must be compared to (currently very expensive) laser-scanning.

Although a great deal has been achieved in this integration of CAD/GIS and photogrammetry and the described system has reached operational capability, there are situations where non-photogrammetric observations are needed to back up the data captured – specifically where it is not possible to get stereo-coverage.

Further efforts should be made in the automatic recognition of primitives for B-rep and CSG representation from digital images. Conversion from octree representation to other geometric representations is a topic which requires further investigation.

Not addressed in this work was the simple but important issue of finding effective and safe facilities for taking photographs from heights. Quite a number of techniques have been tried including hydraulic lifting equipment, scaffolding and ladders. However, optical solutions (including zoom lenses) should also be considered, but this requires further development with regard to the self-calibration of the camera with each photograph.

The only drawback in the approach developed in this work is the requirement for the Photogrammetrist to understand the workings and capabilities of CAD and GIS programs (or vice versa). This is a problem, which can be easily underestimated. A "learning curve", which at times seemed very flat, arose particularly in the preparation of the plans of St Avit Abbey. However, the capacity to accurately digitise a façade feature and then replicate it in other locations provides an extremely powerful tool.

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APPENDIX A

3-D Coordinate Points of the Anobanini Head

C:\DOCUMENTS AND SETTINGS\YOUSEF.SADJADI-C461699
DOCUMENTS\ANOBANINI \DSC02064.JPG

1	-3.59593	3.05991	-17.01893	0.010537	0.013652	0.045204
2	1.81698	2.41795	-17.49712	0.006531	0.016174	0.053536
3	3.23631	-1.55491	-18.27885	0.018539	0.009713	0.074155
4	-2.34627	-2.05949	-18.51337	0.009743	0.006937	0.054105
5	-0.19101	3.43403	-17.04898	0.004068	0.017179	0.048576
6	-2.02759	1.43829	-17.66210	0.009889	0.010394	0.048206
7	4.09949	0.07685	-18.02401	0.030565	0.005552	0.080990
8	2.35263	0.45839	-18.07945	0.016842	0.013154	0.108268
9	0.88864	-2.78997	-18.44790	0.003065	0.010253	0.057194
10	-1.94807	-0.11427	-18.10959	0.010901	0.006504	0.056859
11	-3.45624	-0.46526	-18.14146	0.012647	0.007781	0.056905
14	-3.27316	-3.34089	-18.66256	0.010123	0.010074	0.057763
15	0.39196	1.07747	-17.81455	0.002924	0.016138	0.088464
16	0.52323	2.52644	-17.43276	0.002633	0.016758	0.056874
17	0.75032	2.58213	-17.45175	0.002569	0.016516	0.054912
18	-0.78010	2.83182	-17.22796	0.005370	0.016198	0.050249
19	-1.05365	2.61523	-17.27598	0.006279	0.015457	0.049892
20	-1.65971	2.35349	-17.35939	0.007960	0.013371	0.046219
21	-1.56957	2.12480	-17.44055	0.008140	0.013034	0.048011
22	-1.77330	2.12979	-17.25344	0.008360	0.013663	0.046803
23	-1.95238	2.28817	-17.36513	0.008566	0.012664	0.044638
24	-1.73308	2.26064	-17.42922	0.008272	0.012808	0.046102
25	2.43637	1.57804	-17.56366	0.013029	0.016471	0.070434
26	2.51916	0.88573	-17.93375	0.016132	0.014409	0.090309
28	-1.27882	2.45641	-17.28226	0.006984	0.014898	0.049210
29	-0.61235	3.10552	-17.55290	0.004936	0.014681	0.044855
30	0.11518	1.38812	-17.65353	0.003970	0.017182	0.082311

31	-0.55316	1.90363	-17.63323	0.006006	0.014741	0.059478
32	1.33705	1.15500	-17.68636	0.005526	0.016423	0.087726
33	1.33544	0.90432	-17.52921	0.008316	0.019867	0.114169
34	1.33753	0.68213	-17.59205	0.008390	0.018894	0.120261
39	1.33449	0.41493	-17.41253	0.012880	0.024292	0.169473
41	1.33559	0.17567	-17.40801	0.013211	0.020718	0.163624
43	1.33458	-0.01588	-17.33552	0.016600	0.024451	0.215627
44	1.34001	-0.20903	-17.66668	0.010828	0.014870	0.154100
45	1.30842	2.04282	-17.55774	0.004319	0.016548	0.063392
46	1.49321	1.78305	-17.76533	10.000000	10.000000	10.000000
47	2.19248	1.49760	-17.67553	10.000000	10.000000	10.000000
50	-3.69795	0.09319	-17.95190	10.000000	10.000000	10.000000
51	-3.79221	-2.28310	-18.40201	10.000000	10.000000	10.000000
52	-1.53444	2.56952	-17.36069	10.000000	10.000000	10.000000
53	-1.54160	2.56367	-17.42734	10.000000	10.000000	10.000000
54	-1.54710	2.51962	-17.35123	10.000000	10.000000	10.000000
55	-1.56980	2.52956	-17.36943	10.000000	10.000000	10.000000
56	-1.59000	2.50517	-17.29990	10.000000	10.000000	10.000000
57	-1.63908	2.51698	-17.36662	10.000000	10.000000	10.000000
58	-1.74814	2.62792	-17.74343	10.000000	10.000000	10.000000
59	-1.78290	2.64139	-17.80921	10.000000	10.000000	10.000000
60	-1.77181	2.56411	-17.58642	10.000000	10.000000	10.000000
61	-1.81170	2.57716	-17.66169	10.000000	10.000000	10.000000
62	-1.77747	2.47285	-17.38310	10.000000	10.000000	10.000000
63	-1.79562	2.46867	-17.36824	10.000000	10.000000	10.000000
64	-1.78644	2.40395	-17.16715	10.000000	10.000000	10.000000
65	-1.97586	2.58281	-17.75398	10.000000	10.000000	10.000000
66	-2.03850	2.61695	-17.89737	10.000000	10.000000	10.000000
67	-2.02263	2.53973	-17.67180	10.000000	10.000000	10.000000
68	-2.03893	2.51521	-17.60512	10.000000	10.000000	10.000000
69	-2.10599	2.54806	-17.75058	10.000000	10.000000	10.000000
70	-2.17087	2.56098	-17.84112	10.000000	10.000000	10.000000
71	-2.14181	2.43899	-17.54142	10.000000	10.000000	10.000000
72	-2.18899	2.45098	-17.61108	10.000000	10.000000	10.000000

73	-2.22408	2.44629	-17.62782	10.000000	10.000000	10.000000
74	-2.26905	2.45265	-17.70114	10.000000	10.000000	10.000000
75	-2.26709	2.24570	-17.20607	10.000000	10.000000	10.000000
76	-2.33795	2.27048	-17.35633	10.000000	10.000000	10.000000
77	-2.39615	2.28823	-17.42653	10.000000	10.000000	10.000000
78	-2.56143	2.40884	-17.87563	10.000000	10.000000	10.000000
79	-2.53218	2.33734	-17.66088	10.000000	10.000000	10.000000
80	-2.50763	2.27190	-17.50764	10.000000	10.000000	10.000000
81	-2.59238	2.31472	-17.65730	10.000000	10.000000	10.000000
82	-2.69846	2.37167	-17.88259	10.000000	10.000000	10.000000
83	-2.71887	2.33771	-17.81012	10.000000	10.000000	10.000000
84	-2.78699	2.34278	-17.89751	10.000000	10.000000	10.000000
85	-2.76296	2.27395	-17.74316	10.000000	10.000000	10.000000
86	-2.64701	2.11707	-17.30669	10.000000	10.000000	10.000000
87	-2.60603	2.03622	-17.17812	10.000000	10.000000	10.000000
88	-2.71091	2.10785	-17.54145	10.000000	10.000000	10.000000
89	-2.75844	2.14390	-17.77100	10.000000	10.000000	10.000000
90	-2.68199	2.09043	-17.61766	10.000000	10.000000	10.000000
91	-2.65977	2.13220	-17.61409	10.000000	10.000000	10.000000
92	-2.69441	2.17365	-17.68520	10.000000	10.000000	10.000000
93	-2.66469	2.15434	-17.53936	10.000000	10.000000	10.000000
94	-2.62411	2.16218	-17.52575	10.000000	10.000000	10.000000
95	-2.62151	2.19955	-17.66446	10.000000	10.000000	10.000000
96	-2.53486	2.16897	-17.44154	10.000000	10.000000	10.000000
97	-2.46701	2.14084	-17.30187	10.000000	10.000000	10.000000
98	-2.38967	2.09552	-17.15275	10.000000	10.000000	10.000000
99	-2.39898	2.16420	-17.35610	10.000000	10.000000	10.000000
100	-2.47438	2.28478	-17.73173	10.000000	10.000000	10.000000
101	-2.37616	2.22426	-17.49878	10.000000	10.000000	10.000000
102	-2.35757	2.24356	-17.50457	10.000000	10.000000	10.000000
103	-2.31612	2.22330	-17.42756	10.000000	10.000000	10.000000
104	-2.34203	2.28949	-17.56932	10.000000	10.000000	10.000000
105	-2.19884	2.16168	-17.07247	10.000000	10.000000	10.000000
106	-2.14896	2.14569	-17.00380	10.000000	10.000000	10.000000

107	-2.18845	2.22700	-17.28322	10.000000	10.000000	10.000000
108	-2.13103	2.21135	-17.20912	10.000000	10.000000	10.000000
109	-2.16274	2.29736	-17.41887	10.000000	10.000000	10.000000
110	-2.13993	2.30595	-17.33920	10.000000	10.000000	10.000000
111	-2.11696	2.32210	-17.34004	10.000000	10.000000	10.000000
112	-2.08498	2.32053	-17.33535	10.000000	10.000000	10.000000
113	-2.03847	2.30250	-17.26701	10.000000	10.000000	10.000000
114	-2.03480	2.34719	-17.33414	10.000000	10.000000	10.000000
115	-2.09282	2.47275	-17.69978	10.000000	10.000000	10.000000
116	-2.08448	2.49261	-17.77546	10.000000	10.000000	10.000000
117	-1.95596	2.38866	-17.39936	10.000000	10.000000	10.000000
118	-1.89477	2.37242	-17.33002	10.000000	10.000000	10.000000
119	-1.84595	2.36232	-17.25653	10.000000	10.000000	10.000000
120	-1.85453	2.41856	-17.38984	10.000000	10.000000	10.000000
121	-1.84804	2.46549	-17.53223	10.000000	10.000000	10.000000
122	-1.80869	2.46897	-17.53693	10.000000	10.000000	10.000000
123	-1.74358	2.44789	-17.46273	10.000000	10.000000	10.000000
124	-1.74335	2.48675	-17.60188	10.000000	10.000000	10.000000
125	-1.69917	2.46162	-17.52342	10.000000	10.000000	10.000000
126	-1.65902	2.36748	-17.31928	10.000000	10.000000	10.000000
127	-1.68045	2.37135	-17.52956	10.000000	10.000000	10.000000
128	-1.62282	2.26458	-17.31860	10.000000	10.000000	10.000000
129	-1.62495	2.22860	-17.32901	10.000000	10.000000	10.000000
130	-1.62030	2.21503	-17.45390	10.000000	10.000000	10.000000
131	-1.59150	2.18435	-17.46191	10.000000	10.000000	10.000000
132	-1.60245	2.12325	-17.40813	10.000000	10.000000	10.000000
133	-1.65965	2.18004	-17.55167	10.000000	10.000000	10.000000
134	-1.68857	2.16984	-17.54464	10.000000	10.000000	10.000000
135	-1.75252	2.22710	-17.70089	10.000000	10.000000	10.000000
136	-1.79862	2.26153	-17.76655	10.000000	10.000000	10.000000
137	-1.79308	2.21368	-17.61897	10.000000	10.000000	10.000000
138	-1.76262	2.14768	-17.33187	10.000000	10.000000	10.000000
139	-1.59929	2.10037	-17.47387	10.000000	10.000000	10.000000
140	-1.63256	2.10072	-17.54206	10.000000	10.000000	10.000000

141	-1.72083	2.17182	-17.76395	10.000000	10.000000	10.000000
142	-1.75961	2.19026	-17.77580	10.000000	10.000000	10.000000
143	-1.74742	2.16590	-17.63002	10.000000	10.000000	10.000000
144	-1.82786	2.22488	-17.82395	10.000000	10.000000	10.000000
145	-1.83778	2.18454	-17.74141	10.000000	10.000000	10.000000
146	-1.72533	2.01230	-17.21430	10.000000	10.000000	10.000000
147	-1.80075	2.14353	-17.69313	10.000000	10.000000	10.000000
148	-1.71272	2.06651	-17.46750	10.000000	10.000000	10.000000
149	-1.72692	2.06137	-17.54801	10.000000	10.000000	10.000000
150	-1.67539	1.96996	-17.33699	10.000000	10.000000	10.000000
151	-1.63828	1.94168	-17.27727	10.000000	10.000000	10.000000
152	-1.96568	2.36893	-17.55059	10.000000	10.000000	10.000000
153	-1.88576	2.30839	-17.32798	10.000000	10.000000	10.000000
154	-1.92456	2.39440	-17.61881	10.000000	10.000000	10.000000
155	-1.88286	2.35134	-17.55050	10.000000	10.000000	10.000000
156	-1.88201	2.39579	-17.59558	10.000000	10.000000	10.000000
157	-1.75559	2.25385	-17.21817	10.000000	10.000000	10.000000
158	-1.75477	2.28098	-17.38107	10.000000	10.000000	10.000000
159	-1.82577	2.33316	-17.69134	10.000000	10.000000	10.000000
160	-1.77879	2.20803	-17.24593	10.000000	10.000000	10.000000
161	-1.86757	2.27631	-17.45734	10.000000	10.000000	10.000000
162	-1.89760	2.27581	-17.40279	10.000000	10.000000	10.000000
163	-1.96390	2.31827	-17.54812	10.000000	10.000000	10.000000
164	-2.32986	2.72108	-18.31475	10.000000	10.000000	10.000000
165	-2.30526	2.64901	-18.08684	10.000000	10.000000	10.000000
166	-2.31213	2.62355	-17.93191	10.000000	10.000000	10.000000
167	-2.25434	2.51407	-17.62358	10.000000	10.000000	10.000000
168	-2.25404	2.47744	-17.53801	10.000000	10.000000	10.000000
169	-2.40693	2.60710	-18.00118	10.000000	10.000000	10.000000
170	-2.45750	2.62041	-18.07588	10.000000	10.000000	10.000000
171	-2.54042	2.67094	-18.25864	10.000000	10.000000	10.000000
172	-2.54817	2.61716	-18.14391	10.000000	10.000000	10.000000
173	-2.56559	2.57884	-18.07727	10.000000	10.000000	10.000000
174	-2.52835	2.49607	-17.85382	10.000000	10.000000	10.000000

175	-2.53594	2.45246	-17.72558	10.000000	10.000000	10.000000
176	-2.52327	2.38590	-17.58015	10.000000	10.000000	10.000000
177	-2.55825	2.38927	-17.58039	10.000000	10.000000	10.000000
178	-2.54654	2.33549	-17.42720	10.000000	10.000000	10.000000
179	-2.57824	2.31838	-17.43543	10.000000	10.000000	10.000000
180	-2.62606	2.32679	-17.51059	10.000000	10.000000	10.000000
181	-2.62913	2.27236	-17.37149	10.000000	10.000000	10.000000
182	-2.64830	2.24702	-17.30002	10.000000	10.000000	10.000000
183	-2.61082	2.15589	-17.03799	10.000000	10.000000	10.000000
184	-2.60352	2.09747	-16.90747	10.000000	10.000000	10.000000
185	-2.73012	2.16774	-17.18557	10.000000	10.000000	10.000000
186	-2.79769	2.18146	-17.32805	10.000000	10.000000	10.000000
187	-2.82137	2.15872	-17.33228	10.000000	10.000000	10.000000
188	-2.87383	2.15732	-17.41038	10.000000	10.000000	10.000000
189	-2.87524	2.10431	-17.34476	10.000000	10.000000	10.000000
190	-2.84711	2.10667	-17.19999	10.000000	10.000000	10.000000
191	-2.97633	2.27926	-17.47841	10.000000	10.000000	10.000000
192	-2.90090	2.25129	-17.17996	10.000000	10.000000	10.000000
193	-3.01503	2.36895	-17.45364	10.000000	10.000000	10.000000
194	-2.83438	2.30111	-17.10977	10.000000	10.000000	10.000000
195	-2.76836	2.29644	-17.03710	10.000000	10.000000	10.000000
196	-2.72993	2.31614	-17.03286	10.000000	10.000000	10.000000
197	-2.81626	2.46583	-17.44583	10.000000	10.000000	10.000000
198	-2.79758	2.53082	-17.57727	10.000000	10.000000	10.000000
199	-2.75518	2.55420	-17.57560	10.000000	10.000000	10.000000
200	-2.57580	2.49299	-17.27600	10.000000	10.000000	10.000000
201	-2.56182	2.55363	-17.40833	10.000000	10.000000	10.000000
202	-2.42586	2.46390	-17.12619	10.000000	10.000000	10.000000
203	-2.41002	2.53248	-17.26235	10.000000	10.000000	10.000000
204	-2.32845	2.49501	-17.11341	10.000000	10.000000	10.000000
205	-2.36245	2.60675	-17.39940	10.000000	10.000000	10.000000
206	-2.26649	2.55607	-17.24395	10.000000	10.000000	10.000000
207	-2.29819	2.64683	-17.45803	10.000000	10.000000	10.000000
208	-2.26061	2.65123	-17.45583	10.000000	10.000000	10.000000

209	-2.17534	2.58118	-17.23748	10.000000	10.000000	10.000000
210	-2.09077	2.50455	-17.03283	10.000000	10.000000	10.000000
211	-2.13048	2.60899	-17.31594	10.000000	10.000000	10.000000
212	-2.08000	2.58749	-17.23284	10.000000	10.000000	10.000000
213	-2.07738	2.63587	-17.37634	10.000000	10.000000	10.000000
214	-2.13462	2.75330	-17.74179	10.000000	10.000000	10.000000
215	-2.01250	2.63015	-17.44169	10.000000	10.000000	10.000000
216	-1.51516	2.52832	-17.15111	10.000000	10.000000	10.000000
217	-1.54021	2.55539	-17.14396	10.000000	10.000000	10.000000
218	-1.61565	2.68366	-17.43942	10.000000	10.000000	10.000000
219	-1.62717	2.71561	-17.43727	10.000000	10.000000	10.000000
220	-1.56829	2.66689	-17.22043	10.000000	10.000000	10.000000
221	-1.61882	2.78740	-17.50235	10.000000	10.000000	10.000000
222	-1.62891	2.76969	-17.40706	10.000000	10.000000	10.000000
223	-1.65486	2.74807	-17.34994	10.000000	10.000000	10.000000
224	-1.63784	2.65566	-17.15221	10.000000	10.000000	10.000000
225	-1.68164	2.66863	-17.22246	10.000000	10.000000	10.000000
226	-1.76212	2.68059	-17.29062	10.000000	10.000000	10.000000
227	-1.80681	2.73256	-17.35965	10.000000	10.000000	10.000000
228	-1.81455	2.75482	-17.35814	10.000000	10.000000	10.000000
229	-1.85966	2.75898	-17.43183	10.000000	10.000000	10.000000
230	-1.88679	2.73609	-17.48880	10.000000	10.000000	10.000000
231	-1.87230	2.68244	-17.41939	10.000000	10.000000	10.000000
232	-2.02670	2.84341	-17.97119	10.000000	10.000000	10.000000
233	-2.05614	2.84236	-17.97230	10.000000	10.000000	10.000000
234	-2.05998	2.78441	-17.88563	10.000000	10.000000	10.000000
235	-1.99447	2.57212	-18.24728	10.000000	10.000000	10.000000
236	-2.79845	2.36241	-17.16752	10.000000	10.000000	10.000000
237	-2.89141	2.47462	-17.43348	10.000000	10.000000	10.000000
238	-2.86669	2.47761	-17.36492	10.000000	10.000000	10.000000
239	-2.87449	2.51183	-17.36948	10.000000	10.000000	10.000000
240	-2.94518	2.63354	-17.64262	10.000000	10.000000	10.000000
241	-2.87317	2.60782	-17.46019	10.000000	10.000000	10.000000
242	-2.82324	2.60953	-17.35289	10.000000	10.000000	10.000000

243	-2.76794	2.63155	-17.26706	10.000000	10.000000	10.000000
244	-2.81304	2.73351	-17.48103	10.000000	10.000000	10.000000
245	-2.76907	2.76681	-17.46972	10.000000	10.000000	10.000000
246	-2.68423	2.74728	-17.33007	10.000000	10.000000	10.000000
247	-2.67167	2.79538	-17.39690	10.000000	10.000000	10.000000
248	-2.65695	2.83136	-17.46164	10.000000	10.000000	10.000000
249	-2.63900	2.87025	-17.53816	10.000000	10.000000	10.000000
250	-2.52677	2.80605	-17.31134	10.000000	10.000000	10.000000
251	-2.47640	2.79930	-17.24583	10.000000	10.000000	10.000000
252	-2.29857	2.65978	-16.83451	10.000000	10.000000	10.000000
253	-2.34163	2.78637	-17.16187	10.000000	10.000000	10.000000
254	-2.24130	2.72775	-16.95933	10.000000	10.000000	10.000000
255	-2.22771	2.75608	-17.02106	10.000000	10.000000	10.000000
256	-2.17456	2.75971	-17.02395	10.000000	10.000000	10.000000
257	-2.14087	2.74641	-17.01414	10.000000	10.000000	10.000000
258	-2.07423	2.70204	-16.88957	10.000000	10.000000	10.000000
259	-2.04540	2.72292	-16.95540	10.000000	10.000000	10.000000
260	-2.04572	2.77993	-17.14993	10.000000	10.000000	10.000000
261	-2.08844	2.89299	-17.49077	10.000000	10.000000	10.000000
262	-2.02684	2.83015	-17.36559	10.000000	10.000000	10.000000
263	-1.91442	2.72748	-17.06475	10.000000	10.000000	10.000000
264	-1.97859	2.86502	-17.50083	10.000000	10.000000	10.000000
265	-1.96037	2.86854	-17.58260	10.000000	10.000000	10.000000
266	-1.89911	2.83142	-17.50876	10.000000	10.000000	10.000000
267	-2.83346	2.11527	-17.12705	10.000000	10.000000	10.000000

APPENDIX B

There follow some biographical details [Mackie, 1954], of the text data type accessible from an A/AIS, through linking:

> "William Hunter, the distinguished physician, anatomist and medical teacher was born at Long Calderwood, East Kilbride in 1718. William was a student at the University of Glasgow when he was 13 years old. He went as a medical apprentice to William Cullen, at that time in general practice at Hamilton, and then to Edinburgh University where he attended medical classes. In 1741, William Hunter moved to London where he became a famous anatomist and medical teacher.
>
> > "William Hunter acquired an extensive private collection. Initially his holdings were principally of anatomical and pathological preparations related to his teaching needs, but then these expanded to include books and manuscripts, paintings, ethnographical, botanical, zoological, geological material and coins. In 1766, he bought a house in London to provide a place
> >
> > or his anatomy lectures and his collections. In 1783, William bequeathed the contents of the museum, which he had built up over a number of years in his house in London, to Glasgow University."
>
> "John Hunter, the youngest of William's brothers, was not a formally educated person. John followed his brother, William, south to London when he was 20 years old and quickly acquired a reputation as an anatomist. He made great advances in biological research and built up a second Hunterian Museum, now housed at the Royal College of Surgeons, Lincoln's Inn Fields in London."

Portraits of William and John Hunter

William Hunter (1718-1783)

John Hunter (1728-1793)

APPENDIX C

Geometric Transformations

Geometric transformations convert the positions of points on the 2-D photograph to the 3-D coordinates used to model the 3-D object. But thereafter, once the database has been created, objects are viewed on a screen, and probably one of the most basic graphics operations, then, is the projection of a stored model of a 3-D object onto a 2-D plane.

The algorithms for performing basic computer graphics operations such as geometric transformations may be extended to deal with 3-D objects [Samet, 1990]. The geometric transformation in three-dimensional space can be divided into rotation, translation and scaling.

Rotation in three-dimensional space can be performed about the origin of the coordinate through a specified angle. A rotation in three-dimensional space is executed in the same way as in a two-dimensional space with the addition of the z values. But, rotation in 3-D is much more complex than rotation in 2-D. Three-dimensional rotations require an angle of rotation and an axis of rotation. This axis can be placed anywhere in three-dimensional space, so the axis of rotation need not be horizontal or vertical. The conventional rotations are defined when one of the positive x, y or z coordinate axes is chosen as the axis of rotation. However, the rotation about arbitrary axes may be divided into simple rotation about the three standard coordinate axes. Concerning rotation of † degree about the three regular coordinate axes (x, y, and z), the Equations (6.4), (6.5) and (6.6) can be considered respectively.

$$\begin{vmatrix} x' & y' & z' & 1 \end{vmatrix} = \begin{vmatrix} x & y & z & 1 \end{vmatrix} \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos f & \sin f & 0 \\ 0 & -\sin f & \cos f & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (6.4)$$

$$|x' \ y' \ z' \ 1| = |x \ y \ z \ 1| \begin{vmatrix} \cos f & 0 & -\sin f & 0 \\ 0 & 1 & 0 & 0 \\ \sin f & 0 & \cos f & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (6.5)$$

$$|x' \ y' \ z' \ 1| = |x \ y \ z \ 1| \begin{vmatrix} \cos f & \sin f & 0 & 0 \\ \sin f & \cos f & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (6.6)$$

A translation is used to move an object by a simple shift without converting its orientation. An object is displaced a given distance and direction from its original position. Expressed more precisely, three constants **delta** *x*, **delta** *y* and **delta** *z* are used to compute:

$$\begin{aligned} x' &= x + \mathbf{delta}\ x \\ y' &= y + \mathbf{delta}\ y \qquad (6.7) \\ z' &= z + \mathbf{delta}\ z \end{aligned}$$

whereas, for any point **P** (*x, y, z*) of the object, in order to find its corresponding new point **Q** (*x', y' z'*). The required homogeneous matrix transformation can then be expressed as follows:

$$|x' \ y' \ z' \ 1| = x \ y \ z \ 1 \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \text{delta } x & \text{delta } y & \text{delta } z & 1 \end{vmatrix} \quad (6.8)$$

Scaling an object means changing its size. Although, the dimensions of the object are changed, their proportions remain unchanged. This is called *uniform scaling*. The real number S by which all dimensions are multiplied is called the *scaling factor*. The general case is to apply different scaling factor S_x, S_y and S_z to the three directions of *x*, *y* and *z* of coordinate system. Uniform scaling is the special case of S_x=S_y=S_z=S.

The scale factor S determines whether the scaling is a magnification S >1, or a reduction S <1.

Before the scaling, a fixed point, whose coordinates remains unchanged after the scaling is needed. Scaling with respect to the origin, is effected by the transformation $x' = S_x .x$, $y' = S_y .y$ and $z' = S_z .z$. By using a 4×4 transformation matrix, both local and global scaling can be executed. As shown in equation (6.9), the point **P** (*x*, *y*, *z*, *1*) is scaled to point **Q** (*x'*, *y'*, *z'*, *1*):

$$\begin{vmatrix} x' & y' & z' & 1 \end{vmatrix} = \begin{vmatrix} x & y & z & 1 \end{vmatrix} \begin{vmatrix} S_x & 0 & 0 & 0 \\ 0 & S_y & 0 & 0 \\ 0 & 0 & S_z & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (6.9)$$

APPENDIX D

The Coordinates of the Camera Stations, Targetted and Untargetted Points on the Gilbert Scott Building

Point	X	Y	Z
Origin	30.000	10.000	100.000
S_1	22.001	0.759	99.566
S_2	14.071	0.759	99.608
1001	27.178	12.260	100.926
1002	19.777	14.289	100.948
1003	12.611	14.269	100.936
1004	5.331	12.192	100.942
1005	27.217	12.253	107.159
1006	19.877	14.210	107.459
1007	12.700	14.192	107.472
1008	5.538	14.150	107.440
1009	26.527	12.537	111.517
1010	19.622	14.621	111.698
1011	12.511	14.604	111.699
1012	5.435	14.563	111.656

APPENDIX E

Laser Scanning Systems

Recently 3-D Laser Scanning, or LiDAR, has improved in terms of technology and its field of application. This is an optical measurement method based on the transmission of laser light. The environment is rapidly illuminated point by point and the light is scattered back from the exposed object. The scanner comprises a one-dimensional laser measurement system, for distance, in combination with a mechanical beam deflection system for angular measurements.

Maybe LiDAR is a revolutionary technique in surveying applications, but it may also be complimentary to other methods, such as photogrammetry or total stations. However, in many instances LiDAR may be an easier and more practical way to capture data. It has been used in monitoring deformation of buildings, river banks, cliffs etc. in projects which would have been difficult to complete using traditional methods [Barber and Mills, 2001].

The main output of photogrammetry is vector line drawings. As most engineering, maps, architectural and archaeological applications are setup in this way it needs to be confirmed that LiDAR can deliver this type of product. The data capture cost, whilst high, is not really much more when all considerations, such as reduced data processing time are taken into account.

In the UK LiDAR has been used to monitor railway main lines. The operational rate is between moving video and static surveying techniques. Obviously, static surveying methods are more accurate than moving survey methods [Bryan and Blake, 2000]. In this manner, the high-speed laser provides a very rapid survey of the main line network providing visible data points that can be used for 3-D modelling.

Close-range laser scanning has now been available as a surveying technique for a few years, mainly oriented towards the petrochemical industry and engineering applications [Dallas and Morris, 2002]. Dallas and Morris [2002] consider that the relatively new technique of terrestrial laser scanning should now be of great interest to the surveyors, engineers, architects and archaeologists involved in cultural heritage recording and other structure monitoring applications. Is it now the time to alter the specifications, such as provided by Bryan and Blake [2000] to use such technology? According to Dallas and Morris [2002], photogrammetrists now believe the potential of LiDAR to provide a better result than photogrammetry, in all cases related to buildings, is not yet quite realisable. For example, they have examined the Laser Scanning application at Dunfermline Abbey in Scotland as a historical building and concluded that the previous methods of data capture cannot be replaced by Laser Scanning easily, but the possible application of Laser Scanning to provide the architectural drawings can be considered.